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Picatinny Arsenal
26 July 1945

TECHNICAL REPORT NO. 1550

Effect of Aluminum on the Rate of Detonation of TNT.

By:

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SYNOPSIS

The rates of detonation of mixtures of TNT and aluminum in both the cast and pressed condition have been determined over a wide range of densities and percentages of aluminum. It has been shown that the addition of aluminum to TNT in any proportion up to 40% decreases the rate of detonation. The effect of segregation of the aluminum on the rate of detonation of cast TNT-aluminum mixtures is discussed. The effects of charge diameter and grain size of the TNT component has been investigated for pressed granular TNT-aluminum mixtures.

Five variables have been found to influence the rate of detonation of TNT-aluminum mixtures; the density, charge diameter, percent of aluminum in the mixture, grain size of the aluminum and grain size of the TNT component.

The mechanism of the explosive reaction is discussed. It is argued, based on considerations of blast, burning time, and the amount of oxygen available in the TNT, that the mechanism by which aluminum reduces the rate of detonation of TNT does not consist of an oxidation reaction involving the aluminum. It is postulated that the aluminum remains chemically inert during its passage through the zone of decomposition of the TNT and causes a reduction of the rate of detonation by extracting thermal energy from the reaction zone.

A Theory of Thermal Dilution is proposed which is based on a simultaneous application of the Hydrodynamic Theory, the Theory of Explosive Reactions, and the Theory of Heat Conduction. The theory is shown to be capable of expressing quantitatively the effects of the five parameters on the rate of detonation of TNT-aluminum mixtures. Theoretical calculations have been made and agree within 250 meters per second with experimentally determined rates of detonation.

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Effect of Aluminum on the Rate of Detonation of TNT.

INTRODUCTION:

1. The addition of aluminum to TNT has the effect of greatly increasing the power of the air and water shock waves caused by the detonation of TNT. The tactical advantage in the use of TNT-aluminum mixtures as explosive fillers for bombs and shell lies therefore in the increased blast damage which may result. It is however of importance to determine the effects of additions of aluminum on the rate of detonation of TNT, one of the controlling factors in the fragmentation of bomb and shell casings.

2. Investigations conducted at the Underwater Explosives Research Laboratory of the NDRC at Woods Hole (Ref. F) have shown that the blast effect increases with aluminum content of the TNT-aluminum mixtures to a maximum value when the aluminum content is 30 percent, beyond which further additions of aluminum will result in a decrease in blast pressure. It is also indicated, as a result of tests conducted at this Arsenal (Ref. O), that the brisance of TNT-aluminum mixtures, as measured by the Sand Test, passes through a maximum point with additions of aluminum. The aluminum content of the mixture at which the maximum in the Sand Test occurs is dependent on the amount of the initiating agent used, larger amounts of initiating agent causing the maximum to occur at higher aluminum contents. However, in Fragmentation Tests conducted at this Arsenal (Ref. P), no maximum was observed, additions of aluminum to TNT causing a definite decrease in the ability of TNT to fragment a shell.

3. An investigation of the effect of aluminum on the rate of detonation of TNT has, therefore, been conducted to determine whether a maximum rate is obtained with additions of aluminum to TNT and to determine the magnitude of the increase or decrease in rate of detonation.

4. The report deals with two phases of the detonation problem: (a) an investigation of the effects of the parameters from an experimental point of view with emphasis on the results as applied to actual loading conditions, and (b) an investigation of the theoretical problem of the reaction mechanism involved with applications to the experimental data.

OBJECT:

5. To determine the effect of aluminum on the rate of detonation of cast TNT and pressed granular TNT.

RESULTS:

6. The rates of detonation of cast charges of TNT-aluminum containing from zero to 40 percent of aluminum are presented in Tables I and II. The data in Table I were obtained on castings prepared under carefully controlled conditions, each charge being analysed for aluminum content and X-rayed to determine the presence of blow holes, cavities, and type of crystal structure. The data presented in Table II were obtained on charges which were not as uniform and free from cavities as those in Table I due to segregation of aluminum and the formation of blow holes caused by the mushy condition of the mixtures when poured.

An analysis of the data on cast charges has shown that, in normal pouring practice, the density of the TNT component of a TNT-aluminum mixture approximates 1.57 grams per cubic centimeter. The data in Tables I and II, corrected for density to a density-composition relation in which the density of the TNT component is assumed to be 1.57, are shown plotted in Figure I. The relation between the rate of detonation and composition of the castings is given by the following empirical equation,

$$D_m = 6663 - 3.266\ P - .0269\ P^2$$

in which D_m is the rate of detonation for a density, d_m, given by Equation 3, (Paragraph 12), and P is the percentage of aluminum in the mixture. The form of the empirical expression and the data plotted in Figure I show that the effect of adding aluminum to cast TNT is to continuously decrease the rate of detonation, the effect becoming greater as larger percentages of aluminum are added.

7. Examination of the data on cast TNT-aluminum shows that the rate of detonation becomes more erratic with increase in aluminum content, the mean deviation from the least square rate of detonation-composition relation increasing continuously from 18.9 meters per second for charges containing less than 6 percent of aluminum to 77.1 meters per second for charges containing from 24 to 40 percent of aluminum. The increase in dispersion of the rate of detonation results is accompanied by changes in the crystalline structure of the castings which tend to produce a non-homogeneous structure. The gradation with increasing aluminum content from a fine-grained structure with well dispersed aluminum to a coarse crystalline structure characterized by a pipe of large TNT crystals in the center of the casting and, as evidenced by dark and light blotches of segregation of the aluminum into pockets, is illustrated in Photograph L-28660 of three typical radiographs for castings containing 6, 15, and 25 percent of aluminum. Therefore, although the maximum blast effect is obtained with charges containing 30 percent of aluminum, it is indicated that the difficulty of obtaining uniform and sound castings without severe segregation, increases when the aluminum exceeds 20%.

8. The results of tests to determine the rates of detonation of pressed granular TNT-aluminum mixtures are tabulated in Table III, which is divided into three parts. The first part contains data on charges .992 inch in diameter, the second part contains data on charges 1.102 inches in diameter, and the third part contains data for 1.995 inch charges. The data on one inch charges are shown plotted in Figure II and are expressed by the following empirical equation,

$$D = 1868.8 - 299.4\ P + 0.4724\ P^2 + 3228.6\ d + 161.5\ Pd - 0.4423\ dP^2$$

in which D is the velocity of detonation in meters per second, d is the loading density in grams per cubic centimeter, and P is the percentage of aluminum in the explosive mixture. The data show that at constant loading density, the addition of aluminum decreases the rate of detonation and no maxima are observed in the rate of detonation-composition relationships at constant loading density. The effect of diameter on the rate of detonation of pressed 80/20 Tritonal is shown in Figure III. The charges having 2 inch diameters are observed to detonate at a higher rate than charges having a 1 inch diameter.

9. An analysis of the data on pressed granular TNT-aluminum charges having different diameters and comparison between the results obtained at this Arsenal

and results obtained by the NDRC has shown that the rate of detonation of TNT-aluminum mixtures is affected by five different variables in the following manner:

a. An increase in the radius of the TNT particles decreases the rate of detonation.
b. An increase in the radius of the aluminum particles increases the rate of detonation.
c. An increase in the density of the TNT component increases the rate of detonation.
d. An increase in the diameter of an unconfied cylindrical charge increases the rate of detonation.
e. The rate of detonation at constant charge density decreases with additions of aluminum.

A Theory of Thermal Dilution has been developed which expresses quantitatively the effects of the five variables. The rate of detonation of pressed TNT-aluminum mixtures has been calculated theoretically and agrees within 250 meters per second with the experimentally determined values for the mixtures.

DISCUSSION
OF RESULTS:

Part I. Experimental
A. Cast Charges

10. In evaluating the effects of additions of aluminum on the rate of detonation of cast TNT, it is necessary to choose some rational basis for analysis of the experimental data. From an experimental standpoint, it is not possible to obtain a constant loading density for all mixtures of TNT-aluminum in the cast condition, nor is it always possible to obtain a maximum loading density at all times for all compositions up to that containing 40 percent of aluminum. Density effects on the rate of detonation of castings therefore have considerable bearing on the results of such an analysis. From a practical standpoint, however, it is necessary to evaluate the data with a view towards determining the effect of additions on the rate of detonation of cast TNT at the loading densities which would probably be obtained under actual loading conditions.

11. The density of a TNT-aluminum mixture is given by the following equation,

$$d_m = \frac{1}{A/d_A + (1-A)/d_T} \qquad \text{Eq. 1}$$

in which d_m is the density of the mixture (in grams per cubic centimeter), d_A the crystal density of aluminum, and d_T the loading density of the TNT component in the mixture, the voids in the mixture being included in the calculation of the TNT density. A is the weight fraction of aluminum in the mixture. Substituting the value of 2.70 grams per cubic centimeter (crystal density of aluminum) for d_A, we obtain the following equation for the density of the TNT component,

$$d_T = \frac{2.70\ (1-A)\ d_m}{2.70 - A d_m} \qquad \text{Eq. 2}$$

12. The experimental data on cast mixtures in Table I have been analysed with regard to density of the TNT component, using Equation 2 and it has been

found that the density of the TNT component deviates little from a value of 1.57 for charges containing no aluminum up to mixtures containing 40 percent of aluminum. As the castings were sound and relatively free from porosity, it is assumed that good castings will have a density of the TNT component of 1.57 for purposes of further analysis. From a practical standpoint, therefore, the density-composition curve for cast TNT-aluminum mixtures will be given by the following equation obtained from Equation 1 by substitution of 2.70 for the aluminum density and 1.57 for the density of the TNT component,

$$d_m = \frac{4.239}{2.70 - 1.13\,A} \qquad \text{Eq. 3}$$

The composition-density relation, Equation 3, provides a rational basis for analysis of the rate of detonation data, inasmuch as one variable, the density of the TNT component, has been assumed constant.

13. The following equation has been proposed (Ref. A) for the correction of rates of detonation of TNT and related binary compositions of high explosives for small differences in density,

$$D_2 = D_1 + 3530\,(d_2 - d_1) \qquad \text{Eq. 4}$$

where $\underline{D_1}$ and $\underline{D_2}$ are the rates of detonation for a given explosive at the loading densities d_1 and d_2. The equation is based on the linear rate of detonation-density relation for cast TNT (Ref. B)

$$D = 1131 + 3530\,d \qquad \text{Eq. 5}$$

where $\underline{D}$ is the rate of detonation in meters per second and $\underline{d}$ the loading density in grams per cubic centimeter. Equation 4, based on experimental data for cast TNT, is believed applicable to the correction of rate of detonation data of cast TNT-aluminum mixtures, especially when the fraction of TNT in the mixture is large. It will be shown later that the slope of the rate of detonation-density relations for TNT-aluminum mixtures at constant composition may, under certain conditions, be a function of other variables such as grain size of the ingredients and aluminum content. However, as the density difference, $(d_2 - d_1)$ is, in most cases a small quantity, the use of the value 3530 will incur errors of the order of only a few meters per second and is believed applicable to the correction of cast TNT-aluminum data in view of the large number of experimental values obtained.

14. Equation 4 may then be rewritten, with substitution of Equation 3 for the theoretical loading density, in the following form, for the case of aluminum-TNT mixtures,

$$D_m = D + 3530 \left\{ \left(\frac{4.239}{(2.70 - 1.13\,A)} \right) - d \right\} \qquad \text{Eq. 6}$$

where $\underline{D}$ and $\underline{d}$ are the observed rate of detonation and loading density and $\underline{D_m}$ the rate of detonation corrected to the loading density-composition relation (Equation 3). The corrected rates of detonation are given in Table IV and are shown plotted on Figure 1.

15. The least square quadratic relation for the corrected rate of detonation-composition data is given by

$$D_m = 6663 - 8.266\,P - .0269\,P^2 \qquad \text{Eq. 7}$$

where D_m is the rate of detonation for a density, d_m, given by Equation 3 and P is the percentage of aluminum in the mixture. Equation 7 is shown plotted on Figure 1. Examination of the data shown on Figure 1 and Equation 7 indicates that, in normal pouring practice in which a density of the TNT component of 1.57 is obtained, the effect of adding aluminum to cast TNT is to decrease continuously the rate of detonation, the effect becoming greater as larger percentages of aluminum are added.

16. Although the data indicate that under normal pouring conditions, conditioned by the arbitrary requirement of a 1.57 density of the TNT component, no maximum rate is observed for percentages of aluminum greater than zero, it is possible to load TNT-aluminum charges so that a maximum will be obtained at small percentages of aluminum. The reason for this phenomenon lies in a density effect caused by the cooling conditions required by the pouring procedure. When small quantities of aluminum are added to TNT, the thermal conductivity of the mixture obtained becomes greater than that of pure TNT. As a result, the casting will cool more rapidly and a finer grain structure of the TNT component and resulting higher density of the TNT component will result, thereby causing an increase in the rate of detonation of the cast mixture over that of a pure TNT casting poured at the same temperature and conditions of pre-cooling of the melt. However, as larger amounts of aluminum are added to the melt, the pouring temperature must be increased to obtain sufficient fluidity of the mixture to permit proper pouring. The increase in thermal conductivity of the mixture will then be offset by the increased quantity of heat which must be removed in the solidification of the melt and by the limited heat capacity of the casing or mold. Under such conditions, cooling will become slower and growth of larger crystals, with accompanying decrease in density of the TNT component, will take place. The result will be an additional decrease in rate of detonation caused by the density decrease. X-ray photograph (M-20660 attached) of several charges of different aluminum content show the effect of additions of aluminum on the crystalline structure of the castings.

17. The increased coarseness of the crystalline structure of castings which occurred at high percentages of aluminum was accompanied by the following structural characteristics of the castings:

a. The initial crystallization of the melt at the <u>wall</u> of the mold takes place rapidly and traps aluminum in the interstices of the crystals.
b. The TNT structure becomes oriented rather than random and large crystals are formed, thereby creating a pipe of coarse crystals in the center of the castings.
c. The TNT crystals grow preferentially, excluding aluminum and pushing the aluminum particles ahead of the crystalline boundaries of grain growth into small pockets where many particles may be tightly pressed together.

Two definite effects are caused by the coarseness in structure. First, the resulting structure will be non-homogeneous and the presence of a large crystalline pipe through the center of the casting with a fine grain structure surrounding it will give rise to erratic rates of detonation. This was shown in the case of coarse crystalline pure TNT castings (Ref. B). Second, the segregation of aluminum

into pockets causes the casting to be a non-homogeneous mixture with respect to aluminum and limits the effect of the aluminum in reducing the rate of detonation of TNT. As a result the decrease in rate will be less and the castings will act like a mixture of lower aluminum content.

18. It may be concluded that the coarse crystalline structure will give erratic results and the rate of detonation will be higher than for a fine grain, homogeneous casting. Examination of the corrected rate of detonation of cast TNT-aluminum mixture shows erratic rates of detonation at higher aluminum content, i.e. 20 to 40 percent of aluminum.

19. It is of interest to compare the results for cast 80/20 Tritonal obtained at this Arsenal with results for cast 80/20 Tritonal obtained by the Explosives Research Laboratory of the NDRC at Bruceton. The results obtained by the NDRC are given in Table V and are shown plotted in Figure III. The average rate of detonation obtained by the NDRC on cast charges 1.6 inches in diameter is 6734 meters per second at an average density of 1.748 whereas the rate of detonation of cast 80/20 Tritonal obtained at this Arsenal is, from Equation 7, 6487 meters per second at a density of 1.716. The average rate obtained by the NDRC has been corrected, using Equation 4, to the density obtained at this Arsenal (1.716) with the following results:

Rate of Detonation	Density	Charge Diameter	Source
6621	1.716	1.6 inches	NDRC
6487	1.716	1.0	PA

The NDRC value for 80/20 cast Tritonal is 134 meters per second higher than the value obtained at this Arsenal. The difference is considered outside of the experimental errors of the equipment used to determine the rate of detonation. It is noted, however, that the diameter of the charges used by the NDRC and that used at this Arsenal are different and the difference in rates may be due to a charge diameter effect. A comparable effect on the rate of detonation of increasing the diameter of the charge has been observed experimentally in the case of pressed 80/20 Tritonal (paragraph 23) and it is shown theoretically in Part II of this discussion that increasing the diameter of an unconfined charge of TNT-aluminum will increase the rate of detonation.

B. Pressed Data

20. Although pressed TNT-aluminum mixtures are not used in the general loading of ammunition, pressed mixtures have several advantages over cast mixtures in the study of the effects of the various parameters involved in the detonation mechanism. The effect of variations of density on the rate of detonation mechanism can be studied only in the case of pressed explosives, in which case a wide range of densities may be investigated. A more homogeneous charge can be obtained as segregation of the aluminum is not dependent on crystal growth as in the case of castings and segregation of aluminum due to a difference in density does not take place by settling during the solidification process. In addition, the particle effects of the TNT component can be investigated with pressed explosives as granulation can be controlled.

21. In order to evaluate the effects of density, composition, and granulation, it is necessary to describe quantitatively the relationships between the rate of detonation, density, and aluminum content of pressed granular TNT-aluminum

mixtures. The pressed granular TNT-aluminum data, obtained on 0.992 and 1.102 inch charges, tabulated in Table III, are shown plotted on Figure II. Although the relationships between the rate of detonation and density for different percentages of aluminum are divergent at lower densities, the rate of detonation-density relationships are linear within experimental limits. In view of the variation in the experimental results and the small differences in rate of detonation caused by small additions of aluminum, i.e. 2 percent of aluminum, a statistical study of the data was applied in order to obtain more representative values of the rate of detonation for given densities and aluminum content. Preliminary investigation showed that for a given density range, i.e. 1.45 to 1.46 grams per cubic centimeter, the rate of detonation decreases to a first approximation, decreases linearly with the aluminum content. The least square relations between the rate of detonation and the aluminum content were determined for each density range of 0.01 grams per cubic centimeter for all values in that range, over the total density range of 1.43 to 1.52 grams per cubic centimeter. Rates of detonation were calculated for the midpoint densities from these equations and those values used to calculate linear least square lines for the rate-density relation at constant percentages of aluminum. As there were insufficient data in the higher density range, the linear rate of detonation-composition relationships at constant density could not be calculated for densities greater than 1.52 grams per cubic centimeter. Therefore, in order to apply the condition of linearity to the rate-composition relationship at higher density, the data above 1.52 grams per cubic centimeter density were averaged to obtain an average rate and density for each composition. These average rates of detonation were then corrected for density differences to the average density of all charges above 1.52 density (1.589 grams per cubic centimeter) using the following equation,

$$D_c = D + a\,(1.589 - d) \qquad \text{Eq. 8}$$

where D_c is the corrected rate of detonation at 1.589 density, D the average rate of detonation (uncorrected), d the average density, and a the slopes of the least square rate of detonation-density relationships for constant aluminum composition. The linear least square relationship between rate of detonation and composition was then calculated, using the corrected rates in the upper density group, and least square values for the rate of detonation, at a density of 1.589, were then calculated for different compositions. Finally, least square linear rate of detonation-density relationships for different percentages of aluminum were calculated using the least squares midpoint density rates of detonation from the lower density groups and the least square rates of detonation (at a density of 1.589) for the upper density group of data. The following equations were obtained and are shown plotted in Figure II,

$$D = a_0 + a_1 d \qquad \text{Eq. 9}$$

where D is the rate of detonation and d the loading density of the pressed charge; a_0 and a_1 have the following values:

Percent Aluminum	a_0	a_1
0	1801	3260
2	1303	3515
4	661	3863
6	89	4165
8	- 537	4505
12	- 1703	5125
18	- 3344	5983

Rates of detonation, calculated for densities of 1.40, 1.50, and 1.60 grams per cubic centimeter, are tabulated in Table VI. Examination of the values of a_0 and a_1 shows that they are not linear with percentage of aluminum in the explosive mixture. The following least square equations were therefore calculated for a_0 and a_1:

$$a_0 = 1868.8 - 299.4\ P + 0.4724\ P^2$$

$$a_1 = 3228.6 + 161.5\ P - 0.4423\ P^2$$

Substituting the equations for a_0 and a_1, as functions for the percent aluminum, in Equation 9, the following equation is obtained:

$$D = 1868.8 - 299.4\ P + 0.4724\ P^2 + 3228.6\ d + 161.5\ Pd - 0.4423\ dP^2 \quad \text{Eq. 10}$$

where D is the velocity of detonation in meters per second, d is the loading density in grams per cubic centimeter, and P is the percentage of aluminum in the explosive mixture. The expression may be used to calculate the rate of detonation of pressed granular TNT-aluminum mixtures at any loading density and aluminum content within the range studied.

22. Analysis of the rates of detonation of pressed granular TNT-aluminum mixtures shows that at constant loading density, the addition of aluminum decreases the rate of detonation and no maxima are observed in the rate of detonation-composition relationships at constant loading density. In addition, the effects of additions of aluminum in reducing the rate of detonation of granular TNT are much greater at lower densities. This is shown by the divergence of the linear rate of detonation-density relationships for various aluminum contents, Figure II, and by the variation of the slopes of these lines from 3260 for pure TNT to 5983 for a pressed mixture containing 18 percent of aluminum.

23. Rate of detonation data obtained by the Research Laboratory of the NDRC at Bruceton on pressed granular TNT-aluminum mixtures containing 20 percent of aluminum are tabulated in Table VII and are shown plotted in Figure III. In order to compare the results obtained by the NDRC with results obtained at this Arsenal, the rates of detonation of a 20 percent mixture have been calculated from Equation 10 for densities of 1.40 and 1.60 grams per cubic centimeter. These values and the rate of detonation-density line through them are shown also in Figure III. Comparison of the two sets of data shows that although the results obtained by the NDRC and those obtained at this Arsenal agree closely at a density of approximately 1.65, the results differ widely at lower densities, those obtained at this Arsenal being lower than the NDRC results. Thus, whereas the difference in rates of detonation is 119 meters per second at a density of 1.60, the difference is 579 meters per second at a density of 1.40, or approximately five times greater. These differences are well outside of the error of determination of the rates of detonation and must be dependent upon the variables of the detonation mechanism. Two definite differences in the experimental charges used are noted:

a. The diameter of the pressed charges used by the NDRC varied from 1.25 to 2.0 inches whereas the diameter of the charges fired at this Arsenal was approximately 1 inch.
b. The grain diameter of the TNT used by the NDRC in preparing the mixtures was approximately 15 microns whereas the TNT grain diameter used at this Arsenal was much larger, the TNT having been used in the "as received" condition.

The effect of variations in the diameter of the charges is shown by comparison of the data obtained at this Arsenal on 1 and 2 inch diameter charges of pressed 80/20 Tritonal, the least square relationships of which are shown plotted in Figure III. The increase in diameter is observed to increase the rate of detonation. The discrepancy between the results obtained by the NDRC and at this Arsenal is not attributable to inherent errors in the methods used in the determination of the rate of detonation (Ref. A) but may be caused by the grain size of the TNT component. It is indicated, therefore, that differences between the two sets of data are due to differences in diameter of the charges and variations in the grain size of the TNT component. In this connection, it is noted that the screen analysis of the aluminum used by the NDRC and at this Arsenal is the same and as a result, the rates of detonation do not show any effect due to grain size of the aluminum.

C. Comparison of Cast and Pressed TNT-aluminum Mixtures

24. The rate of detonation of cast TNT is lower for a given loading density than the rate for pressed granular TNT. The rate of detonation-density relationship for both types of charges are approximately parallel, the rate of detonation of pressed TNT being given by Equation 9,

$$D = 1801 + 3260\, d$$

and the rate of detonation of cast TNT by Equation 5,

$$D = 1131 + 3530\, d$$

At a loading density of 1.60, cast TNT has a rate of detonation 238 meters per second lower than that of pressed granular TNT. It is interesting to compare the rates of detonation of cast and pressed TNT-aluminum mixtures to determine if equal reduction in rates is observed for equal percentages of aluminum in the mixtures.

25. As the upper densities of the pressed data are less than the densities of the cast mixtures, it is necessary to correct the data to the same loading density. In the case of pressed explosives, it has been pointed out that although the effect of grain size of the TNT is small at high densities, at low densities the effect is large. The extrapolation of data for pressed charges to densities higher than those at which charges have been fired is, therefore, affected by the grain size effects at low density and might lead to considerable error. However, when grain size has little effect on the rate of detonation at low densities, it is found, as in the case of the NDRC results, that the rate of detonation-density relationships for various TNT-aluminum compositions are approximately parallel to the relationship for pure TNT. It is thus believed appropriate to correct the cast TNT data to a constant loading density in the upper density region of the pressed TNT-aluminum data, i.e. 1.60 grams per cubic centimeter, using a constant slope for the rate of detonation-density relationships.

26. The rate of detonation of cast TNT-aluminum mixtures is given by Equation 7,

$$D_m = 6663 - 8.266\, P - .0269\, P^2$$

at a loading density given by Equation 3,

$$d_m = \frac{4.239}{2.70 - 1.13\,A}$$

Equation 4 may be rewritten in the form

$$D_{1.60} = D_m + 3530\,(1.60 - d_m) \qquad \text{Eq. 11}$$

where $D_{1.60}$ is the rate of detonation at a density of 1.60. Substituting Equations 7 and 8 in Equation 11, and letting P/100 = A, the following equation is obtained,

$$D_{1.60} = 12311 - 8.266\,P - .0269\,P^2 - \frac{14964}{2.70 - .0113\,P} \qquad \text{Eq. 12}$$

The rates of detonation of cast and pressed TNT-aluminum mixtures have been calculated from Equations 12 and 9, respectively, and are shown plotted in Figure 4. It is observed that the effect of additions of aluminum in reducing the rate of pressed TNT is greater than for cast TNT. The difference of 230 meters per second between pure cast and pressed TNT decreases to 40 meters per second for a mixture containing 20 percent of aluminum. At higher percentages of aluminum, it is indicated from Figure IV that pressed mixtures will detonate at a lower rate of detonation than cast charges.

27. Non-homogeniety of the mixture caused by central piping, growth of large crystals, and segregation of aluminum into isolated pockets apparently has the effect of limiting the ability of aluminum to reduce the rate of detonation of cast TNT. In the case of pressed mixtures, in which a more homogeneous mixture is obtained and aluminum is well dispersed within the interstices of the TNT structure, the aluminum is better able to affect the reaction mechanism of the detonation wave and thus causes a greater reduction in rate of detonation than in the case of cast TNT.

Part II. Theoretical

28. It has been shown experimentally that, both in the case of cast and pressed granular TNT-aluminum mixtures, additions of aluminum at constant loading density decrease the rate of detonation of TNT. In addition, it has been observed that the ability of aluminum to reduce the rate of detonation of TNT is dependent on four variables:

a. Loading density of the charge.
b. Percentage of aluminum in the mixture.
c. Grain size of TNT component.
d. Diameter of charge.

Data on the effect of varying the granulation of the aluminum on the rate of detonation of TNT are not available. The effect of granulation of the aluminum in reducing the rate of detonation of EDDN (Ethylenediamine dinitrate) and PETN has been determined by the NDRC for a PETN-aluminum mixture containing 15 percent of aluminum and for a EDDN-aluminum mixture containing 13 percent of aluminum (Ref. D) with the following results:

Explosive	Density	Rate	Av. Particle Size of Aluminum (in microns)
85/15:PETN/Aluminum	1.526	7025	150
	1.517	6740	10
87/13:EDDN/Aluminum	1.440	6580	150
	1.426	6390	50
	1.421	6240	10

The data indicate that the effect of reducing the grain size of the aluminum is to reduce the rate of detonation of the mixture. Although it has not been shown that the grain size of aluminum will affect the rate of detonation of TNT-aluminum mixtures, it will be assumed that granulation of the aluminum is a variable in the detonation mechanism of TNT-aluminum mixtures.

29. Two hypotheses have been proposed to explain the action of aluminum in reducing the rate of detonation of TNT;

a. The aluminum reacts with the products of decomposition of the TNT to form aluminum oxide and the rate of detonation of TNT-aluminum mixtures can be calculated by means of the hydrodynamic theory of detonations.

b. The action of aluminum in reducing the rate of detonation of TNT consists in a thermal dilution mechanism in which energy is removed from the explosive reaction in heating the aluminum.

Both hypotheses predict a decrease in the rate of detonation of TNT with additions of aluminum. However, as the chemical reaction hypothesis is based on the hydrodynamic theory which is independent of grain size, the chemical theory is incapable of explaining the effects of those variables. The thermal hypothesis is purely qualitative in its stated form and when based on the hydrodynamic theory is also incapable of expressing the effects of grain size and charge diameter.

30. In order to determine the plausability of either hypothesis it is necessary to examine the implications of the hypotheses in view of experimental data, not only from the standpoint of the rate of detonation but other phenomena associated with the detonation, i.e. blast measurements and flash duration measurements.

31. The decomposition reaction for TNT, as postulated by the hydrodynamic theory is

$$C_7H_5\ (NO_2)_3 = 6\ CO + 2\tfrac{1}{2}\ H_2 + C + 1\tfrac{1}{2}\ N_2$$

Assuming that aluminum reacts completely with the oxygen to form aluminum oxide and all of the oxygen is exausted from the decomposition products, the reaction could be represented by the equation:

$$C_7H_5\ (NO_2)_3 + 4\ Al = 7\ C + 2\tfrac{1}{2}\ H_2 + 1\tfrac{1}{2}\ N_2 + 2\ Al_2O_3$$

The condition of 4 moles of aluminum per mole of TNT is satisfied in a TNT-aluminum mixture containing 32.2 percent of aluminum. Further addition of aluminum can not, therefore, result in reduction of the rate of detonation of a 32.2 percent mixture as oxygen is not available for the reaction with aluminum. It has been shown experimentally, however, that the rate of detonation of a TNT-aluminum mixture containing 40 percent of aluminum is lower than that of a 32 percent mixture. The chemical hypothesis is, therefore, not capable of explaining the effects of aluminum when present in quantities greater than 32.2 percent.

32. The results of blast measurements on TNT-aluminum mixtures obtained by the British (Ref. F) are tabulated below, the blast measurement being given as the ratio of the average impulse to that of TNT:

Bomb Filler	Average Impulse Ratio to TNT
TNT	1.00
90/10 TNT/Al	1.18
85/15 TNT/Al	1.20
80/20 TNT/Al	1.26
75/25 TNT/Al	1.30
70/30 TNT/Al	1.37
65/35 TNT/Al	1.33
60/40 TNT/Al	1.28

The impulse of the shock wave resulting from the detonation of TNT-aluminum increases with additions of aluminum to TNT up to a maximum value for a mixture of approximately 30 percent of aluminum.

33. It has been shown (Ref. G) that a charge of Torpex-2, TNT/RDX/Al; 40/42/18 has an impulse indistinguishable from that of a charge composed of a core of Composition B, comprising 70 percent of the weight of the charge, and a surround of TNT/Al; 40/60, comprising the remaining 30 percent of the charge weight. The overall composition of the cored charge is that of Torpex-2. In the case of Torpex-2, therefore, the explosive may be separat[illegible] its component parts without affecting the blast performance of the [illegible] appreciably. This has been accounted for by the hypothesis that after-burning occurs and results in an increase of the energy of detonation.

34. Further support of the hypothesis of after-burning is given by the results of blast measurements on SBX charges composed of a bursting charge of 64/40 granular TNT/magnesium surrounded by a charge of 2 pounds of flake aluminum, (Ref. H). The amount of oxygen available for combustion of the after-products of the detonation was varied by the amount of opening in the closed chamber, large and small, and by firing in the open. The effect of varying the available oxygen on the peak pressure, impulse, and duration of positive impulse is shown in the following table (Ref. H):

Venting	Pressure (lbs./sq.in.)	Impulse (lb.-millisec./sq.in.)	Duration (millisec.)
Open	2.0	10	10
Large	4.1	194	88
Small	4.2	421	170

In addition, the pressure-time curves show the contribution of the combustible surround by the superposition of a smooth hump on the pressure-time curve of the burster. It may then be concluded that the aluminum burns in the atmosphere after the detonation wave has passed and is affected by the amount of oxygen in the air. The combustion of the aluminum takes place over a considerable length of time and has been estimated to be only about one third complete when burning ceases.

35. The results of intensity and duration of flash tests conducted at this Arsenal using TNT and 92/8; TNT/aluminum for shell filler (Ref. I) showed that the addition of 8 percent of aluminum to TNT increased by 58 percent the total duration of flash resulting from the detonation of TNT.

36. It is concluded from the results of blast measurements and flash duration

measurements that the aluminum in a TNT/aluminum mixture is present, immediately following the passage of the detonation wave, predominantly as metallic aluminum. It is further concluded that the aluminum reacts at a later time, several times the length of time required for the charge to detonate completely, with the oxygen of the atmosphere and perhaps with the products of decomposition of the TNT. In view of these conclusions, the validity of the reaction theory as an explanation of the effect of aluminum on the rate of detonation of TNT is questionable. The thermal theory of reaction mechanism is far more valid as the data presented do not contradict this theory. On the other hand, the rapid burning of the aluminum in the atmosphere following the detonation requires heating of the aluminum to the ignition temperature before reaction takes place.

37. In view of the evidence against the chemical reaction hypothesis and the plausibility of the thermal dilution hypothesis, the latter will be assumed to be the primary mechanism resulting in the decrease in the rate of detonation of TNT with additions of aluminum. The thermal hypothesis, although previously proposed, does not postulate any condition which controls the amount of heat extracted by the aluminum particles during the reaction period. An extension of the thermal hypothesis is presented here which is capable of explaining, within the right order of magnitude, the effects on the rate of detonation of TNT-aluminum of the five observed parameters, namely, grain size of TNT, grain size of aluminum, charge diameter, loading density of mixture, and aluminum content of mixture. The theory is based on the following three basic concepts:

a. Hydrodynamic theory of detonation waves.
b. Theory of explosive reactions.
c. Theory of heat flow into a cold sphere from a constant heat reservoir.

Hydrodynamic Theory

38. The progress of a detonation through a charge of explosive is measured by the velocity along the charge of the zone of chemical reaction which takes place. This velocity is called the detonation velocity. The reaction zone immediately behind the detonation front, in which the explosive decomposes and the products are formed, is characterized by an immediate and very large increase in pressure and temperature. The detonation products also acquire a high forward velocity. The time required for the explosive to react essentially to completion is so short that the zone of reaction, under favorable conditions, is very narrow. As a consequence, a mathematical plane dividing the unreacted explosive from the zone in which reaction is taking place and travelling along the charge with the detonation velocity, D, is followed very closely by a plane dividing the reaction zone and the completely reacted gases. For purposes of mathematical analysis, the reaction is assumed to take place so fast that the thickness of the reaction zone is infinitesimal.

39. The theoretical derivation of the equations from which the detonation velocity may be calculated is dependent upon the conditions across the discontinuity, i.e. the boundary between the unreacted explosive and the detonation products. Five basic conditions are applied to the discontinuity:

a. The law of conservation of mass.
b. The law of conservation of momentum.
c. The law of conservation of energy.
d. The conditions of the entropy function.
e. The ideal gas law.

As a result, two equations are obtained which enable one to calculate the detonation velocity provided the gaseous products act like a perfect gas (Ref. J):

$$\frac{\frac{1}{2} n_2 R T_i}{\gamma i} = Q + \bar{C}_i (T_i - T_o) \qquad \text{Eq. 13}$$

$$D_i = (\gamma_i + 1) \sqrt{\frac{n_2 R T_i}{\gamma_i M}} \qquad \text{Eq. 14}$$

in which the symbols have the following significance:

- D_i - the detonation velocity (in meters per second) assuming that the products act like a perfect gas.
- T_i - the temperature of the products (in degrees absolute).
- T_o - the initial temperature of the explosive (in degrees absolute).
- M - the gram molecular weight of the explosive.
- n - the number of moles of gaseous products formed from M grams of explosive.
- R - the gas constant in the ideal gas law.
- Q - the heat of reaction at constant volume (heat absorbed) per M grams of explosive at the initial temperature, T_o.
- γi - the ratio of the specific heats of the products of decomposition at constant pressure to constant volume at the temperature of the products, T_i.
- $\bar{C}_i$ - the mean heat capacity of M grams of the burnt gases at constant volume from temperature T_o to T_i.

If Q, n, and M are known, the dependence of $\bar{C}_i$ and γ_i on the temperature T_i is known, and reaction is assumed to proceed quantitatively so that shifts in the equilibrium of the products do not affect the dependence of n and Q on the temperature T_i. Then the temperature T_i and the ideal rate of detonation, D_i, may be calculated from Equations 13 and 14.

40. The calculation of the ideal rate of detonation is seen to be independent of density of the charge. The high pressures which are encountered in detonations of solid high explosives cause the gas relations to depart radically from those of the ideal gas and a dependence of detonation rate on density of explosive is always observed. An equation of state has been proposed which will account for the behavior of the gaseous products of decomposition of high explosives at high temperatures and pressures and has the following form (Ref. J):

$$PvM = n R T (1 + x e^{b x}) \qquad \text{Eq. 15}$$

in which $x = K / T^a v M$,

where $a = 0.25$, $b = 0.3$

and $\underline{v}$ is the specific volume of the products at the detonation temperature T, $\underline{P}$ is the detonation pressure in the burnt gases, and $\underline{K}$ is the covolume of the gaseous products at the temperature T. It is found that $\underline{x}$ is proportional to the loading density of the explosive. The analysis of the fundamental equations, using the imperfect gas law, Equation 15, leads to the conclusion that the ratio of the theoretical detonation rate, $\underline{D}$, calculated using the imperfect gas law, to the ideal detonation rate, $\underline{D_i}$, is a function of $\underline{x}$ and therefore of the loading

density, d, of the explosive. Therefore, a knowledge of T_i, D_i, and the co-volume constant K, enables one to calculate the theoretical detonation rate, D, for any loading density, d.

41. In accordance with the hydrodynamic theory, a decrease in the heat of reaction, Q, will result in a decrease in the temperature T_i and T, and in D_i and D for a given loading density. The theory of thermal dilution and its effect on the rate of detonation of TNT-aluminum mixtures postulates that thermal energy is extracted by the aluminum particles in the mixture during the time of decomposition of the explosive. The effect of extracting energy during the reaction is to decrease the heat of reaction and we may then define a new heat of reaction

$$Q' = Q - \Delta Q \qquad \text{Eq. 16}$$

in which ΔQ is the quantity of heat extracted by the aluminum per mole of explosive and Q' is the quantity of thermal energy remaining in the reaction zone which is available for increasing the temperature of the reaction products. The quantity Q' must be used in Equation 13 in the calculation of the theoretical detonation rate, D, when thermal energy is extracted during the reaction. The detonation velocity, D, and the detonation temperature T_i at four loading densities for assumed values of ΔQ have been calculated for TNT. The results are tabulated in Table VIII and are shown plotted in Figure V.

Theory of Explosive Reactions

42. It is observed that the hydrodynamic theory does not consider the effects of grain size, confinement, or diameter of a bare charge. In particular, the hydrodynamic theory postulates a condition such that the ratio of the thickness of the zone of reaction to that of the charge diameter is very small. Such would be true for any finite length of reaction zone when the explosive extends infinitely in the reaction plane, normal to the direction of the detonation wave. From a practical standpoint, perfect confinement is not obtained and in the case of bare charges having no confinement, effects of charge diameter and grain size have been observed. The theory of explosive reactions partially explains the effects of grain size and confinement of charge and enables calculation of two quantities which are required in the solution of the TNT-aluminum problem; namely, the length of the zone of reaction, and the time of reaction.

43. As the detonation wave proceeds through an explosive charge, decomposition of the explosive takes place in the zone of reaction. The reaction starts at some point in the zone, presumably the front of the detonation wave, and continues to some other point at which the reaction is completed. From a practical standpoint, the reacting explosive has a finite size, i.e. a grain of explosive, and the decomposition will therefore occur during a finite time interval. The condition of a finite length of reaction zone does not invalidate the results of the hydrodynamic theory because, under conditions of inifinite charge extent or complete confinement and a finite charge diameter, application of the hydrodynamic analysis between the two points, beginning and end of the reaction zone, will yield the same result. The hydrodynamic rate of detonation is therefore the rate of detonation which an explosive will have under conditions of perfect confinement.

44. The decomposition reaction in a detonating explosive takes place at a

definite rate and may be calculated by means of absolute reaction rate theory (Ref. K and L). Two reaction mechanisms have been proposed (Ref. K) for explosive detonations:

a. A homogeneous reaction in which the reactant decomposes to the product gases directly through formation of activated molecules of the reactant.
b. A surface or two thirds order reaction in which the reactant vaporizes and reaction then proceeds in the vapor phase to form the products.

An analysis has shown that mechanism (a) is not likely, inasmuch as the reaction must start at the surface of a grain. Thermal conduction is inadequate to heat the interior of a grain during the reaction time and the interior will not be heated sufficiently to cause it to decompose. In addition, the work done by a shock wave front on a particle is not sufficient to raise the temperature of a grain high enough so that the reaction could take place homogeneously. In the case of the surface reaction, (b), the sensitivity of the detonation to particle size requires a dependence on grain size or surface area, thus necessitating that the vaporization process be the rate controlling factor. The reaction rate equation then becomes that of the vaporization reaction and has the form:

$$\frac{d\,(\text{products})}{dt} = k\,(\text{surface}) \qquad \text{Eq. 17}$$

where (product) and (surface) refer to the molecular concentration in the vapor phase and solid surface. The absolute reaction rate for the vaporization reaction is

$$k = \frac{KT}{h}\, e^{-\Delta F/RT} \qquad \text{Eq. 18}$$

in which k is the specific reaction rate constant, ΔF the standard free energy change for a mole of activated complex from the reactants, K is Boltzmann's constant, h is Plank's constant, T the absolute temperature, and R is the gas constant. Applying Equation 18 to the vaporization process (Eq. 17) we obtain the differential equation (Ref. K)

$$-\frac{dm}{dt} = g\,\frac{S}{s}\,\frac{KT}{h}\, e^{-\Delta F/RT} \qquad \text{Eq. 19}$$

in which

m - the number of molecules in one gram of solid.
g - the number of explosive grains per gram of solid.
S - the surface area of one grain.
s - area occupied by one molecule.

Letting

$$M = n\, m_0$$
$$g = 3\, V_0/4\pi r_0^3$$
$$S = 4\pi r_0^2\, n^{2/3}$$
$$s = (V_0/m_0)^{2/3}$$

where m_0 - the initial number of molecules per gram in the solid.
V_0 - the specific volume of a grain
r_c - the initial radius of a grain
n - the fraction of unreacted material,

the time to completion is obtained by solving Equation 19 between the limits 1 to

zero for n, and 0 to t_1 for t. The following equation is obtained:

$$t_1 = r_o \frac{h}{KT} \left(\frac{m_o}{V_o}\right)^{1/3} e^{\Delta F/RT} \qquad \text{Eq. 20}$$

In a stable wave, the time of reaction is given approximately by the time required for the detonation wave to traverse the length of the reaction zone, a_1, or

$$t_1 = a_1 / D \qquad \text{Eq. 21}$$

Substituting Equation 21 in Equation 20, we obtain

$$a_1 = r_o D \frac{h}{KT} \left(\frac{m_o}{V_o}\right)^{1/3} e^{\Delta F/RT} \qquad \text{Eq. 22}$$

Analysis of the equation using values pertinent to TNT shows that a good approximation to Equation 24 is given by

$$a_1 = r_o e^{\Delta F/RT} \qquad \text{Eq. 23}$$

which will be assumed in calculations of the length of the reaction zone. The equation shows that to a first approximation, a_1 is directly proportional to the grain radius, r_o, and that the length of the reaction zone depends greatly on the detonation temperature, T.

45. Although the time for the detonation wave to travel the length of the reaction zone, a_1, is given by Equation 21 with reference to a fixed observer, the reacting particle is travelling in the same direction as the wave and spends a longer time in the zone of reaction. The true time of reaction, t_1, which is the time for the particle to remain in the reaction zone, has been shown to be (Ref. L) given to a first approximation by

$$t_1 = \frac{a_1 d_1}{D d} \qquad \text{Eq. 24}$$

in which d_1/d is the ratio of the density of the products at the end of the zone of reaction to the loading density. The ratio d_1/d can be calculated from the hydrodynamic theory. From Equations 23 and 24, it is seen that a_1 depends on the grain size and temperature but is independent of the density, whereas, t_1 is dependent on the loading density, d, through the rate of detonation, D.

46. Values of a_1 have been calculated using various assumed values of the grain radius and the temperatures corresponding to the values of ΔQ used in the hydrodynamic calculations and tabulated in Table VIII. The results are included in Table IX and are shown plotted in Figure VI. In calculating a_1 the value of ΔF was taken to be 22500 calories per mole, which has been proposed as a result of several types of analyses of the rate of detonation of TNT (Ref. L). As the detonation temperature, T, varies little with density and from the ideal temperature, T_i, T_i has been used throughout the calculations.

Heat Conduction Theory

47. It has been shown that if a certain quantity of thermal energy is removed from an explosive reaction, the rate of detonation of the explosive will be reduced. In addition to the reduced rate of detonation, the detonation tem-

perature, the time of reaction, and the length of the reaction zone can be calculated using the hydrodynamic theory and theory of explosive reactions. In order to solve the TNT-aluminum problem, it is necessary to determine the quantity of heat which will be extracted from the reaction zone by the aluminum. The problem becomes that of determining how much thermal energy the aluminum particles can absorb during the reaction time and at the detonation temperature. The following assumptions are made in the application of the heat conduction equations:

a. The aluminum particles are spherical.
b. The aluminum particle is subjected to the detonation temperature throughout the interval of time it is in the reaction zone.
c. The aluminum particle is assumed to be in the zone of reaction during the time t_1.
d. The coefficient of surface resistance to heat conduction at the solid-gas interface is negligible.
e. The extraction of heat by the aluminum particle after it leaves the reaction zone will not further affect the reaction and therefore the rate of detonation.

48. If a sphere of conducting material at a uniform temperature is instantaneously subjected to a high temperature, heat will flow from the surroundings into the sphere and raise the temperature. The problem is one of heat conduction in the unsteady-state and has been solved by means of Fourier series analysis (Ref. m). The solution is given in the following form:

$$u = T + \frac{2C}{\pi r}(T_o - r)\left[e^{\frac{-a^2\pi^2}{C^2}} \sin\frac{\pi r}{C} - \frac{1}{2} e^{\frac{-4a^2\pi^2}{C^2}t} \sin\frac{2\pi r}{C} + 1/3\, e^{\frac{-9a^2\pi^2}{C^2}t} \sin\frac{3\pi r}{C} \; \ldots\right] \qquad \text{Eq. 25}$$

in which $\underline{u}$ is the temperature at any point $\underline{r}$ distance from the center of the sphere, $\underline{c}$ is the radius of the sphere, T_o and T are the initial temperature of the sphere and temperature of surroundings (detonation temperature), $\underline{t}$ is the reaction time, and $\underline{a^2}$ is the thermal diffusivity, C_p is the specific heat of aluminum and d_a is the density of aluminum. The quantity of heat absorbed by the particle in time t is

$$H = \int_o^v d_a\, C_p\, (u - T_o)\, dv \qquad \text{Eq. 26}$$

in which $\underline{v}$ is the volume of the particle. The solution of Equation 26 is

$$H = 4\pi d_a C_p \left(\frac{T}{3} C^3 + \frac{2C^3(T_o-T)}{\pi^2} e^{\frac{-a^2\pi^2}{C^2}t} + \frac{C^3(T_o-T)}{2\pi^2} e^{\frac{-4a^2\pi^2}{C^2}t} + \frac{2}{3}\,\frac{C^3(T_o-T)}{\pi^2} e^{\frac{-9a^2\pi^2}{C^2}t}\right) - \frac{4}{3}\pi C_p d_a C^3 T_o \qquad \text{Eq. 27}$$

As the weight of one grain of aluminum is

$$W = \frac{4}{3}\pi C^3 d_a$$

the number of grains per mole of aluminum is given by

$$N = M / (4/3)\ c^3\ d_a \qquad \text{Eq. 28}$$

where M is the molecular weight of aluminum. The quantity of heat absorbed by one mole of aluminum particles will then become

$$Q_a = H\ N \qquad \text{Eq. 29}$$

Values of Q_a have been calculated for aluminum particles of 25 and 50 microns radius and temperatures, T, of 3000 and 2000°K. for various values of t_1. The following numerical values were assumed:

$$a^2 = .7781 \text{ sec.}^{-1}$$
$$C_p = .2595 \text{ cal /gram-}^\circ\text{C.}$$
$$d_a = 2.70 \text{ grams/cc.}$$
$$T_o = 300^\circ\text{K.}$$

The results of the calculations are tabulated in Table X and are shown plotted in Figure VII.

Theory of Thermal Dilution

49. The solution to the calculation of the effect of aluminum on the rate of detonation of TNT lies in the simultaneous solution of the hydrodynamic equations, the reaction theory equations, and the heat conduction equation. As the hydrodynamic calculations are based on the quantity of heat extracted per mole of TNT, it is necessary to express the results of the heat conduction equations in the same manner. The moles of aluminum per mole of TNT is given by the following relation,

$$\theta = M\ A / M_a\ (1 - A) \qquad \text{Eq. 30}$$

in which M and M_a are the molecular weights of TNT and aluminum, and A is the weight fraction of aluminum in the mixture. The heat extracted by the aluminum particles in the mixture is then

$\theta\ Q_a$ calories per mole of TNT.

The solution of the problem requires the following equalities:

Theory	Heat conduction theory
Hydrodynamic	$\Delta Q = \theta\ Q_a$
Hydrodynamic	$T_i = T$
Explosive reaction	$t_1 = t$

From the value of ΔQ and the relationship between ΔQ and D which is shown plotted on Figure V, the rate of detonation, D, may be calculated. The value of the rate of detonation, D, which is obtained is the hydrodynamic rate and is only to be obtained under conditions of complete confinement or infinite extent of the explosive charge.

50. In considering the case of explosives of low energy, i.e. amatol, ammonium picrate, and TNT, the ratio of the length of the reaction zone, a_1, to

the charge radius, r. is large and a considerable portion of the energy of detonation is dissipated laterally. Under given conditions of charge diameter and explosive grain size, the decrease in temperature of detonation caused by additions of a thermal diluent (aluminum) causes an increase in the length of the reaction zone, thereby accentuating the effects of lateral expansion. In particular, in the case of no confinement such as is present in firings of a bare charge, if the decomposition reaction in particular region of the zone of reaction has only gone to partial completion when the expansion occurs, the remaining reaction will take place as if the initial density of loading of the explosive were less, thereby affecting the pressure and temperature of the reaction zone and resulting in a lower rate of detonation than the rate of detonation obtained with complete confinement, D. Unless the temperature decrease is so great that the reaction temperature will not be sufficient to cause decomposition of the explosive and therefore cause failure of the wave to propogate, the rate of detonation will decrease from the hydrodynamic rate of detonation, D, to some lower velocity, D_s, called the stable rate of detonation. Analysis of the problem from the standpoint of explosive reaction theory (Ref. L) has resulted in an approximate equation relating the hydrodynamic rate of detonation, D, to the stable rate, D_s, in terms of the length of the reaction zone, a_1 and the charge radius, r. The equation has the form,

$$D_s = D\,(1 - a_1/2r) \qquad \text{Eq. 31}$$

The stable rate of detonation is measured when bare charges are fired and is the theoretical rate of detonation which it is desired to calculate for comparison of theoretical and experimental results.

Method of Calculation

51. The method of calculating the stable detonation rate, D_s, will be demonstrated assuming a charge composed of an 80/20: TNT/Al mixture, containing TNT grains having an average particle radius of .0025 cm. (25 microns) and aluminum particles having an average radius of 25 microns, a charge diameter of one inch (2.54 cm.) and a loading density of 1.50 grams per cubic centimeter. From the hydrodynamic theory, values of ΔQ, T_1, and D are obtained for a density of 1.50 grams/cc. (Table VIII). The quantity d_1/d is also calculated from the hydrodynamic theory for a density of 1.50. The results are tabulated as follows:

ΔQ (Cal./mole)	T_1 (°K)	D (meters/sec.)	d_1/d
0	2904	6882	1.303
6400	2800	6826	1.302
12070	2700	6755	1.301
19000	2600	6682	1.301
25030	2500	6608	1.299
37070	2300	6455	1.297
50000	2100	6296	1.295
62040	1900	6143	1.292

From the reaction rate theory, (Equation 23 for the length of the reaction zone, a_1, and Equation 24 for the time of reaction) we obtain the following values:

ΔQ Cal./mole	T_i (°K)	D (meters/sec.)	a_1 (cm.)	t_1 (microsec.)
0	2904	6882	.1251	.2369
6400	2800	6826	.1447	.2760
12070	2700	6755	.1682	.3240
19000	2600	6682	.1978	.3851
25030	2500	6608	.2355	.4631
37070	2300	6455	.3497	.7026
50000	2100	6296	.5599	1.152
62040	1900	6143	.9897	2.081

The heat conduction equation (Equation 27) is now evaluated for the above corresponding values of T and t, and the quantity of heat extracted per mole of aluminum, Q_a (Equation 29), is obtained. From Equation 30 the value of θ, the moles of aluminum per mole of TNT, is obtained and the quantity of heat absorbed per mole of TNT, θQ_a, then calculated. The results of the heat conduction calculations are as follows:

T (°K)	t (microsec.)	Q_a (cal./mole)	θQ_a (cal./mole)
2904	.2369	8710	18330
2800	.2760	8990	18910
2700	.3240	9300	19570
2600	.3851	9550	20090
2500	.4631	9770	2056[illegible]
2300	.7026	10330	21730
2100	1.152	10720	22550
1900	2.081	10640	22390

The two sets of results are now solved simultaneously for the conditions

$$Q = \theta Q_a$$
$$t_1 = t$$

When $t_1 = t$, the method of calculation also requires that $T_i = T$. The solution has been obtained graphically and is shown in Figure VIII. The value of Q obtained is 19,700 calories per mole of TNT. From Figures V and VI, the corresponding values of $D = 6666$ and $a_1 = .205$ are obtained. From these values and Equation 31, the stable rate of detonation, $D_s = 6128$ is obtained.

52. The theoretical stable rates of detonation, D_s, have been calculated for TNT-aluminum mixtures containing from zero to 30 percent of aluminum, assuming values of 25 and 50 microns for the radius of the aluminum particles and values of 16, 25, 40 and 55 microns for the average radius of the TNT particles. The calculations have been made assuming one inch and two inch diameter charges which are completely unconfined. It is to be noted that the density used in the calculations is that of the TNT component, d_T. The results of the calculations are plotted in the following manner in order to show the effects of the various parameters on the rate of detonation of TNT-aluminum mixtures from a theoretical point of view:

Figure IX. The rate of detonation-density relationships for TNT-aluminum mixtures are plotted for various percentages of aluminum and assumed values of 25 microns for the radius of the aluminum particles and 55 microns for the radius of the TNT particles. The curves are typical for all mixtures and show the parallelism

between lines of various aluminum content.

Figure X. The relationship between the rate of detonation and radius of the TNT particles at constant aluminum content is shown for various percentages of aluminum, assuming mixtures containing aluminum particles of 25 and 50 microns radius. The density of the TNT component of the mixture is assumed constant (1.57 grams/cc.).

Figure XI. The relationship between the rate of detonation and particle radius of the TNT component is shown for various percentages of aluminum in the mixtures and charge diameters of 1 and 2 inches. The density of the TNT component is constant (1.57 grams/cc.) and the radius of the aluminum particles is assumed to be 25 microns.

53. It is seen from Figure IX that the effect on the rate of detonation of TNT-aluminum mixtures increases with successive additions of aluminum. This is shown by the following values (Figure IX) of the decrease in rate of detonation with successive additions of 10 percent of aluminum:

Decrease in Rate of Detonation (meters/sec.)	Aluminum Content
346	0 to 10 percent
628	10 to 20 percent
1335	20 to 30 percent

The effect of increasing the radius of the TNT particles on given mixtures of TNT-aluminum is shown in Figures X and XI.

54. It is interesting at this point to examine the effects of variations in particle radius of the aluminum and TNT and charge diameter on the rate of detonation of 80/20: TNT/aluminum mixtures. The effect of varying the aluminum particle size is shown in Figure 10. The following table shows the decrease in rate of detonation of TNT caused by additions of 20 percent of aluminum for mixtures containing the following size of particles:

Radius of TNT Particle (in microns)	Decrease in Rate of Detonation (meters per second)	
	Radius of Aluminum Particle	
	25 microns	50 microns
50	875	420
25	422	180

It is to be noted that although mixtures containing particles of either 25 or 50 microns radius show the same decrease in rate of detonation (420 meters per second) the actual rate of detonation of the mixture composed entirely of particles of 50 microns radius is 348 meters per second lower than that containing particles of 25 microns radius. In the extreme comparison the above mixtures, the mixture composed of 25 microns radius aluminum and 50 micron radius TNT has a rate of detonation which is 1045 meters per second lower than that composed of 50 micron radius aluminum and 25 micron radius TNT.

55. In the case of 80/20: TNT/aluminum charges having diameters of 1 and 2 inches (Figure XI) the following tabulation shows the effects of varying the charge diameter and radius of TNT particles:

Radius of Aluminum Particle (microns)	Decrease in Rate of Detonation (meters per second)	
	Diameter of Charge	
	1 inch	2 inch
25	425	315
50	375	530

In the extreme case, the rate of detonation of a 1 inch diameter charge composed of TNT particles having a 50 micron radius is 1035 meters per second lower than a 2 inch charge composed of TNT particles of 25 micron radius.

56. It is thus observed that the theory of thermal dilution proposed and outlined in this report is capable of qualitatively describing the effects of the five parameters and predicts the following:

a. An increase in the radius of the TNT particles decreases the rate of detonation of a TNT-aluminum mixture.
b. An increase in the radius of the aluminum particles increases the rate of detonation of a TNT-aluminum mixture.
c. An increase in the diameter of an unconfined cylindrical charge increases the rate of detonation of a TNT-aluminum mixture.
d. An increase in the density of the TNT component increases the rate of detonation of a TNT-aluminum mixture.
e. The rate of detonation of a TNT-aluminum mixture at constant density of the TNT component decreases with additions of aluminum.

Part III. Interpretation of Experimental Results

57. It has been shown that the Theory of Thermal Dilution, proposed and outlined in Part II of this report, is capable of explaining qualitatively the effects of the various parameters on the rate of detonation of TNT-aluminum mixtures. It remains to determine whether the theoretical quantitative results compare within reasonable limits with experimentally observed rates of detonation. The data obtained using pressed TNT-aluminum charges having diameters of 1 and 2 inches and varying in both aluminum content and loading density provided a means for establishing the quantitative value of the theory.

58. As the theoretical rates of detonation are calculated on the basis of the density of the TNT component in the mixture, d_T, it is necessary to express the observed rates of detonation in terms of the TNT component density. The rates of detonation of charges having a 1 inch diameter and containing 0, 10, and 20 percent of aluminum and charges having a diameter of 2 inches containing 0 and 20 percent of aluminum are shown plotted in Figure XIV as a function of the density of the TNT component. The data shown in Figure XIV show two differences from the relationships predicted by the Theory of Thermal Dilution:

a. The experimental rate of detonation-density relationships, diverge at lower densities whereas the theory predicts that all rate of detonation-density relationships, in which the grain size and charge diameter are maintained constant, are parallel lines having a slope of 3040 meters per second.
b. The 2 inch diameter charges of pure TNT have lower rates of detonation than 1 inch diameter charges of pure TNT.

It is evident, however, that the rate of detonation-density relationship obtained by the ERDC using 1.5 inch diameter charges of pressed 80/20 Tritonal is more nearly parallel to the relationships for pure TNT. This may be explained by the fact that the average diameter of the TNT used in preparing the charges was extremely small (approximately 20 microns) and the effects of variations of grain size of the TNT component in progressing from a low to high density is small.

59. The charges used at this Arsenal were prepared from granular TNT in the "as received" condition. The material is prepared by a graining process which produces a fairly uniform coarse particle size. In general, the granular TNT before pressing will not pass a U.S.Standard 120 mesh screen. It may be assumed that the average particle size of the TNT in the "as received" condition is the same as when the TNT occupies the minimum volume obtainable without further consolidation, i.e. the bulk density of the material. Further consolidation requires that the void spacings be filled with TNT to provide a higher loading density and therefore requires that the material be comminuted, thereby reducing the average particle size. The phenomenon will continue until, at the crystal density of the TNT, the particles are of molecular size or may be assumed to be of zero diameter. It is not known what the relationship between density and particle size is but a few assumptions may be made which will not introduce large errors.

a. The density-particle size relation is linear in character and satisfies the particle size value at the bulk density and the requirement of infinitesimal particle size at the crystal density.
b. The density-particle size relation is independent of the aluminum content of a TNT-aluminum mixture and is based on the density of the TNT component in the pressed condition.

As a preliminary method of testing these assumptions, the average particle size of the TNT was determined for both the unpressed material and pellets of TNT having two different densities and 2 inch diameters. The following data were obtained (the particle size of the loose material being correlated with the bulk density):

Density (grams/cc.)	Radius of Average Particle, r_o (microns)
.83	107
1.352	56
1.575	47

The linear relation between the density and particle radius, r_o, calculated from the particle radius at the bulk density and the crystal density of TNT (1.65 grams/cc.) is

$$r_o = 216 - 132\, d_T \qquad \text{Eq. 32}$$

The determined particle sizes of the pelleted material agree within 15 microns with values given by the linear relation.

60. As a further step in the theoretical analysis, it was decided to determine the theoretical particle size of the TNT component which would produce

a given observed value of the rate of detonation. The procedure required knowledge of the average particle radius of the aluminum component in the mixtures. Screen analysis of the aluminum particles before pressing showed the material to be comprised 23 percent of particles varying from 44 to 149 microns in diameter and 77 percent with a diameter less than 44 microns. The average particle diameters were determined by means of a Fisher Sub-sieve Sizer, microscopic examination, and from the screen analysis of the material. Values of 13.6, 16.3, and 19.7 microns, respectively, were obtained. However, in view of the large percentage of particles varying from 44 to 149 microns in diameter and the tendency of fine material to ball together and thus form a single particle of larger effective diameter from a thermal standpoint, the average diameter of the aluminum particles has been chosen, as an approximation, to be 50 microns for use in the theoretical analysis.

61. The theoretical particle sizes of the TNT component in TNT-aluminum mixtures have been calculated by means of the Theory of Thermal Dilution and various observed rates of detonation. The following results were obtained:

Percent Aluminum	Density, d_T (grams/cc.)	Radius of Particle (microns) Charge diameter (inches) 1	2
0	1.60	16	52
	1.50	17	55
	1.40	7	31
10	1.53	31	-
	1.44	42	-
	1.32	57	-
20	1.202	49	63
	1.328	35	50
	1.426	25	40
	1.478	20	31
	1.540	14	24

The values obtained from data on 2 inch diameter charges agree closely with values by Equation 32. The values for the particle size obtained from data on 1 inch charges are approximately 10 microns lower than given by Equation 32 but tend towards zero at the crystal density. The particle size of the TNT used in preparing the 1 inch diameter charges was not determined as material was not available but it is indicated, from the fact that the 1 inch diameter charges had higher rates of detonation than the 2 inch diameter charges, that the particle size of the material used in preparing the 1 inch diameter charges was slightly less than of the material used in preparing the 2 inch charges.

62. Although it is indicated that the two lots of TNT used varied in particle size it is possible to obtain quantitative theoretical values of the rates of detonation by assuming that the particle size of the TNT satisfies the particle size-density relationship given by Equation 32. The rate of detonation-density (TNT component) relations have been calculated theoretically, using Equation 32, for 1 inch charges containing 0, 10 and 20 percent of aluminum and 2 inch charges containing 0 and 20 percent of aluminum are shown plotted in Figure XV. The same divergence of the rate-density lines is observed as was obtained experimentally. The 2 inch diameter charges have a higher rate of detona-

tion than the 1 inch charges as is to be expected as the linear density-grain size equation prescribes a larger TNT grain size than was present in the 1 inch charges and a slightly smaller grain size than was present in the ... inch charges which were used in the determinations of the rates of detonation. However, it is seen that the theoretical and observed rates of detonation, for all mixtures, agree within 250 meters per second and it is indicated that, with more accurate data concerning the TNT grain size parameter, closer agreement of the theoretical and observed rates may be obtained. It is therefore concluded that the Theory of Thermal Dilution is capable of predicting the rate of detonation of a pressed TNT-aluminum mixture within 3 to 4 percent if the values of the various parameters are accurately known.

63. Figures XII and XIII show the theoretical relationships between the rate of detonation and particle radius of the TNT component for assumed values of the aluminum particle radius of 25 microns, a charge diameter of 1 inch, and various percentages of aluminum for two densities of the TNT component. These relationships are useful for calculating the effects of the various parameters on the rate of detonation of TNT-aluminum mixtures.

CONCLUSIONS:

64. Additions of aluminum to TNT, either in the cast or pressed condition, reduce the rate of detonation of TNT.

65. The presence of segregation of the aluminum component of cast TNT-aluminum mixtures caused by formation of large TNT crystals reduces the effects of additions of aluminum on the rate of detonation of TNT.

66. Five variables may affect the rate of detonation of a TNT-aluminum mixture, namely, the loading density, the percent of aluminum in the mixture, diameter of a bare explosive charge, and the average grain size of the aluminum and TNT components. Whereas increases in the radius of the aluminum particles, the diameter of an unconfined cylindrical charge, and of the density of the charge result in increased rates of detonation, additions of aluminum or an increase in the radius of the TNT particles result in lower rates of detonation of TNT-aluminum mixtures.

67. The mechanism by which additions of aluminum reduce the rate of detonation of TNT does not consist of a reaction in which aluminum is oxidized but consists of absorption of thermal energy by the aluminum particles in the reaction zone during the time in which the TNT is decomposing. The Theory of Thermal Dilution, which is based upon the Hydrodynamic Theory, The Theory of Explosive Reactions, and equations of heat conduction for a metallic sphere in the unsteady state, is capable of predicting the rate of detonation of a TNT-aluminum mixture within 250 meters per second.

EXPERIMENTAL PROCEDURE:

68. Mixtures of TNT and aluminum (Grade B) were cast into charges 20 inches long and 1 inch in diameter, approximately. The mixtures were poured in the mushy condition so as to minimize segregation of the aluminum. Two samples of each casting, one from each end, were analysed for aluminum content and the value for the charge assumed as the average of the two. All charges were X-rayed

for blow holes, pipes, cavities, and other defects including segregation of the aluminum in the charges and poor castings were rejected. The charge densities were calculated from the length, diameter, and weight of the charges. The charges were spirally wrapped with a double thickness of .005 inch thick cellulose acetate sheet and were initiated by means of four Tetryl pellets (density approximately 1.50 grams per cubic centimeter, 0.995 inch in diameter and 0.75 inch long, three solid pellets and one pellet with central hole to receive a blasting cap), placed at one end of the charge and a Corps of Engineers Blasting Cap.

69. Granular TNT was blended with aluminum powder (Grade B) to form batches containing 0, 2, 4, 6, 8, 12 and 18 percent of aluminum. The mixtures were then pressed into pellets having diameters of .992 inch and 1.102 inch and a length of .750 inch approximately. The pellets were divided into weight groups of 40 milligrams range and those groups in turn into length groups of .003 inch range. The resulting pellets, varying in density by approximately plus or minus .005 grams per cubic centimeter, were assembled into sticks of 25 pellets each and secured with longitudinal strips of Scotch Tape. The sticks were then wrapped and boostered in the same manner as the cast charges.

70. Pellets having a diameter of 1.995 inches and a length of .75 inch were pressed from a mixture of granular TNT (Lot WD-501) and Grade B aluminum containing 0 and 20 percent of aluminum. The pellets were pressed at the lowest and highest densities at which good pellets could be obtained. Sticks were prepared containing 18 pellets each and secured with a longitudinal wrapping of Scotch Tape. The charge densities were calculated from the length, diameter, and weight of the charges. The charges were wrapped and boostered in the same manner as the cast charges with the exception that two Tetryl pellets (1.5 inches in diameter by .50 inch long) were interposed between the end of the charge and the .995 inch diameter Tetryl pellets of the initiating system.

71. The rates of detonation of the cast charges and pressed charges having diameters of .992 and 1.102 inches were determined by means of the high speed rotating drum camera equipment at this Arsenal (Ref. N). The rate of detonation of the 1.995 inch diameter charges was determined by means of the d'Autriche Method.

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Table I

Cast TNT-Aluminum Data

Percent Aluminum	Density gm./cc.	Rate meters/sec.	[illegible] Record No.
5.35	1.603	6602	607
5.20	1.603	6579	608
4.75	1.607	6643	609
4.85	1.607	6640	610
4.25	1.601	6652	611
4.35	1.605	6660	612
3.30	1.598	6695	613
3.40	1.596	6709	614
5.55	1.606	6620	615
8.60	1.628	6634	616
8.70	1.636	6704	617
7.90	1.628	6576	618
8.95	1.629	6565	619
8.00	1.626	6623	620
8.95	1.638	6573	621
9.40	1.635	6501	622
9.20	1.639	6553	623
8.45	1.626	6567	624
9.45	1.642	6669	625
9.65	1.641	6625	626
8.80	1.638	6857	627
9.00	1.609	6614	628
8.95	1.639	6643	629
8.55	1.642	6651	630
9.35	1.651	6669	631
7.80	1.636	6683	632
7.55	1.634	6675	633
9.35	1.636	6631	634
9.10	1.635	6579	635
11.70	1.665	6773	636
11.95	1.673	6738	637
11.30	1.675	6640	638
11.60	1.659	6643	639
12.60	1.664	6628	640
11.75	1.664	6596	641
10.65	1.637	6611	642
14.95	1.667	6466	643
13.65	1.666	6489	644
15.40	1.664	6469	645
14.95	1.658	6527	646
13.65	1.655	6342	647
15.40	1.673	6455	648
15.95	1.673	6518	649
14.60	1.665	6402	650

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Table I (continued)

Percent Aluminum	Density gm./cc.	Rate meters/sec.	Firing Record No.
19.60	1.702	6371	652
18.15	1.706	6365	653
19.95	1.720	6504	654
18.80	1.711	6478	655
19.80	1.699	6339	656
19.10	1.697	6452	657
20.85	1.703	6376	658
19.40	1.701	6411	659
25.70	1.759	6388	660
24.20	1.754	6449	661
25.85	1.768	6628	662
25.60	1.762	6475	663
23.25	1.745	6353	664
25.20	1.744	6347	665
24.35	1.736	6292	666
26.35	1.750	6272	667

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Table II

Cast TNT-Aluminum Data

Percent Aluminum	Density	Rate	Firing Record
30	1.807	6443	524
	1.798	6313	525
	1.798	6492	526
	1.798	6344	527
	1.788	6301	528
	1.801	6336	529
	1.807	6375	530
	1.787	6295	531
	1.806	6460	532
	1.798	6417	533
	1.803	6408	534
	1.796	6510	535
40	1.883	6191	536
	1.889	6255	537
	1.881	6255	538
	1.901	6353	539
	1.898	6356	540
	1.901	6423	541
	1.899	6443	542
	1.901	6397	544
	1.884	6423	545
	1.861	6469	546

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Table III

Pressed TNT-Aluminum Data

1. Pellet diameter .992 inch

Percent Aluminum	Density	Rate	Firing Record
0	1.438	6565	668
	1.444	6515	669
	1.452	6573	670
	1.461	6602	671
	1.467	6657	672
	1.469	6570	673
	1.471	6631	674
	1.475	6669	675
	1.477	6617	676
	1.479	6637	677
	1.484	6657	678
	1.488	6631	679
	1.492	6625	680
	1.496	6678	681
	1.500	6663	682
2	1.434	6266	683
	1.438	6246	684
	1.442	6304	685
	1.446	6327	686
	1.450	6379	687
	1.455	6420	688
	1.459	6420	689
	1.488	6504	690
	1.492	6472	691
	1.496	6512	692
	1.500	6623	693
	1.500	6533	694
	1.505	6588	695
	1.505	6547	696
	1.509	6541	697
	1.513	6646	698
4	1.450	6185	699
	1.455	6272	700
	1.459	6226	701
	1.463	6313	702
	1.467	6307	703
	1.484	6411	704
	1.488	6423	705
	1.492	6391	706
	1.496	6431	707
	1.501	6417	708

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Table III (continued)

Percent Aluminum	Density	Rate	Firing Record
6	1.425	6061	709
	1.430	6014	710
	1.434	6127	711
	1.438	6005	712
	1.442	6078	713
	1.446	6130	714
	1.451	6078	715
	1.455	6145	716
	1.459	6182	717
	1.475	6292	718
	1.488	6284	719
	1.492	6339	720
8	1.484	6191	721
	1.488	6202	722
	1.488	6200	723
	1.492	6208	724
	1.492	6165	725
	1.496	6301	726
	1.496	6118	727
	1.501	6286	728
	1.501	6234	729
	1.505	6191	730
	1.505	6214	731
	1.505	6220	732
	1.509	6255	733
	1.509	6210	734
	1.513	6397	735
	1.513	6321	736
	1.517	6385	737
12	1.429	5724	738
	1.434	5759	739
	1.438	5759	740
	1.442	5759	741
	1.446	5785	742
	1.450	5823	743
	1.454	5771	744
	1.463	5808	745
	1.471	5841	746
	1.475	5858	747
	1.479	5843	748
	1.484	5930	749
	1.488	5921	750
	1.492	5916	751
	1.496	5939	752
	1.501	6011	753
	1.509	6052	754
	1.517	6058	755
	1.522	6017	756

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Table III (continued)

Percent Aluminum	Density	Rate	Firing Record
18	1.434	5203	757
	1.438	5244	758
	1.442	5220	759
	1.442	5232	760
	1.446	5223	761
	1.446	5249	762
	1.446	5296	763
	1.446	5290	764
	1.450	5302	765
	1.451	5270	766
	1.455	5342	767
	1.455	5348	768
	1.455	5351	769
	1.458	5302	770
	1.459	5362	771
	1.459	5223	772
	1.459	5333	773
	1.463	5391	774
	1.463	5397	775
	1.463	5362	776
	1.467	5417	777
	1.468	5443	778
	1.471	5446	779
	1.472	5374	780
	1.476	5423	781
	1.480	5446	782
	1.480	5524	783
	1.484	5541	784
	1.488	5504	785
	1.501	5681	786

2. Pellet diameter 1.102 inch

Percent Aluminum	Density	Rate	Firing Record
0	1.551	6733	862
	1.554	6770	863
	1.554	6799	864
	1.554	6799	865
	1.554	6909	866
	1.558	6912	867
	1.558	6811	868
2	1.561	6846	869
	1.561	6744	870
	1.565	6857	871
	1.565	6747	872
	1.565	6834	873
	1.568	6904	874
	1.568	6817	875

Table III (continued)

Percent Aluminum	Density	Rate	Firing Record
4	1.568	6773	876
	1.571	6695	877
	1.571	6686	878
	1.571	6753	879
	1.571	6799	880
	1.571	6707	881
	1.575	6762	882
	1.575	6756	883
	1.575	6634	884
6	1.575	6643	885
	1.575	6701	886
	1.578	6721	887
	1.578	6712	888
	1.578	6675	889
	1.578	6724	890
	1.582	6762	891
	1.582	6709	892
	1.582	6709	893
	1.585	6704	894
8	1.588	6672	895
	1.588	6663	896
	1.588	6620	897
	1.592	6640	898
	1.592	6738	899
	1.592	6602	900
	1.595	6625	901
	1.595	6625	902
12	1.611	6524	903
	1.615	6579	904
	1.615	6567	905
	1.615	6643	906
	1.618	6530	907
	1.618	6623	908
	1.622	6481	909
18	1.640	6426	910
	1.643	6449	911
	1.643	6440	912
	1.643	6481	913
	1.643	6437	914
	1.646	6423	915
	1.646	6397	916
	1.650	6397	917
	1.650	6480	918

Table III (continued)

3. Pellet diameter 1.9[illegible] inch

Percent Aluminum		Density	Rate	[illegible] Record
0		1.339	6020	1475
		1.326	6076	1476
		1.323	6023	1477
		1.335	6020	1478
		1.318	5977	1479
		1.324	6055	1480
		1.330	6034	1481
	Av.	1.328	6030	
0		1.484	6850	D61*
		1.475	6450	D62
		1.434	6590	D63
		1.472	6540	D64
		1.479	6220	D65
		1.480	6560	D66
		1.480	6680	D67
		1.472	6120	D68
	Av.	1.478	6499	
20		1.328	5000	D54
		1.304	4760	D55
		1.367	4970	D56
		1.407	4940	D57
		1.338	4826	D58
		1.397	5050	D59
		1.324	4677	D60
	Av.	1.352	4889	
20		1.576	6200	D76
		1.531	5930	D77
		1.577	5870	D78
		1.576	5966	D79
		1.580	6034	D80
		1.564	6087	D81
		1.573	6150	D82
	Av.	1.575	6034	

* The letter D indicates that the rate of detonation was determined using the d'Autriche Method.

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Table IV

Cast Rates Corrected for Density to Composition Density Curve in Which the TNT Component Density is 1.57.

Percent Aluminum	Corrected density gm./cc.	Rate (corrected) meters/sec.	Firing Record No.
5.35	1.606	6613	607
5.20	1.605	6536	608
4.75	1.602	6625	609
4.85	1.603	6626	610
4.25	1.599	6645	611
4.35	1.600	6642	612
3.30	1.590	6667	613
3.40	1.593	6693	614
5.55	1.608	6627	615
8.60	1.629	6638	616
8.70	1.630	6683	617
7.90	1.624	6562	618
8.95	1.632	6576	619
8.00	1.625	6619	620
8.95	1.631	6548	621
9.40	1.634	6497	622
9.20	1.633	6532	623
8.45	1.628	6574	624
9.45	1.635	6644	625
9.65	1.636	6607	626
8.80	1.630	6829	627
9.00	1.632	6695	628
8.95	1.632	6618	629
8.55	1.629	6605	630
9.35	1.634	6609	631
7.80	1.624	6641	632
7.55	1.622	6633	633
9.35	1.634	6624	634
9.10	1.632	6568	635
11.70	1.650	6720	636
11.95	1.652	6604	637
11.30	1.648	6542	638
11.60	1.650	6611	639
12.60	1.657	6603	640
11.75	1.651	6550	641
10.65	1.643	6632	642
14.95	1.674	6491	643
13.65	1.665	6485	644
15.40	1.678	6518	645
14.95	1.674	6583	646
13.65	1.665	6377	647
15.40	1.678	6473	648
15.95	1.682	6550	649

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Table IV (continued)

Percent Aluminum	Corrected density gm./cc.	Rate (corrected) meters/sec.	Firing Record No.
14.60	1.672	6427	650
14.40	1.670	6378	651
19.60	1.710	6399	652
18.15	1.699	6340	653
19.95	1.713	6479	654
18.80	1.704	6453	655
19.80	1.712	6385	656
19.10	1.706	6434	657
20.85	1.720	6436	658
19.40	1.709	6439	759
25.70	1.759	6388	660
24.20	1.746	6421	661
25.85	1.760	6600	662
25.60	1.758	6465	663
23.25	1.738	6318	664
25.20	1.754	6382	665
24.35	1.747	6331	666
26.35	1.764	6321	667
30	1.795	6401	524
	1.795	6302	525
	1.795	6481	526
	1.795	6333	527
	1.795	6326	528
	1.795	6315	529
	1.795	6333	530
	1.795	6323	531
	1.795	6421	532
	1.795	6407	533
	1.795	6380	534
	1.795	6506	535
40	1.886	6184	536
	1.886	6244	537
	1.886	6273	538
	1.886	6300	539
	1.886	6314	540
	1.886	6370	541
	1.886	6397	542
	1.886	6344	544
	1.886	6430	545
	1.886	6451	546

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Table V

Rate of Detonation of Cast 80/20 TNT-Aluminum
Obtained by NDRC.

Diameter of Charge	Density	Rate	Reference
1.6"	1.759	6780	(c)*
	1.759	6775	
	1.760	6750	
	1.725	6660	
	1.735	6705	
1.75"	1.370	5040	(d)**
1.625"	1.396	5070	
	1.403	5050	

* Secondary aluminum (94.4% Al) varying in size from 1 to 150 microns, averaging 60 microns.

** Aluminum bronze powder, 1-20; 10 average microns.

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Table VI

Least Square Rates of Detonation of Pressed TNT-Aluminum Mixtures.

Percent Aluminum	Rate of Detonation, meters per second Density (grams/cc.) 1.40	 1.50	 1.60
0	6365	6691	7017
2	6224	6576	6927
4	6069	6456	6840
6	5920	6337	6753
8	5770	6221	6671
12	5472	5985	6407
18	5032	5631	6229

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Table VII

Rate of Detonation of Pressed Granular TNT-Al. Mixture
Containing 20% Al. Obtained by NDRC.

Diameter of Charge	Av. TNT	Av. Al. Size	Density	Rate	Ref.
	1-40	1-150			
1.25"	10M	60M	1.564	6060	(C)*
			1.615	6305	
			1.611	6285	
			1.559	6100	
			1.432	5575	
	1-80	1-100			
1.6"	20 M	Av. 50 M	1.654	6505	(D)**
			1.657	6440	
	1-40	1-100			
1.25"	15	Av. 50	1.061	4170	(E)**
			1.138	4425	
			1.228	4740	
2.0"			1.186	4575	
			1.218	4645	
			1.397	5320	

* Secondary Al. (94.4% Al.).
** Navy specification aluminum; 1-100 microns; Av. 50 by microscopic count.

Screen analysis
100% through 100 mesh (149M)
15% plus 325
85% through 325 mesh (44M)

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Table VIII

Calculations of Detonation Velocity D for TNT for Various Quantities of Heat Extracted, ΔQ.

ΔQ (cal./mole of TNT)	T_i (°K)	D (meters per second) Density (g./cc.) 1.57	1.50	1.40	1.30
0	2904	7165	6882	6507	6143
6400	2800	7100	6826	6446	6080
12070	2700	7031	6755	6374	6010
19000	2600	6960	6682	6302	5944
25030	2500	6891	6603	6229	5873
37070	2300	6738	6455	6027	5724
50000	2100	6576	6296	5920	5565
62040	1900	6426	6143	5763	5409

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Table IX

Calculated values of the Length of the Reaction Zone, A_1, for TNT.

ΔQ (cal./mole.)	T_i (°K.)	A_1 (in cm.) Grain radius, r_o (in microns)				
		16	25	40	55	70
0	2904	.0805	.1251	.2002	.2753	.3504
6400	2800	.0932	.1447	.2316	.3184	.4053
12070	2700	.1083	.1682	.2691	.3700	.4710
19000	2600	.1273	.1978	.3164	.4351	.5337
25030	2500	.1516	.2355	.3769	.5182	.6595
37070	2300	.2251	.3497	.5596	.7694	.9792
50000	2100	.3603	.5599	.8958	1.231	1.568
62040	1900	.6369	.9897	1.583	2.177	2.771

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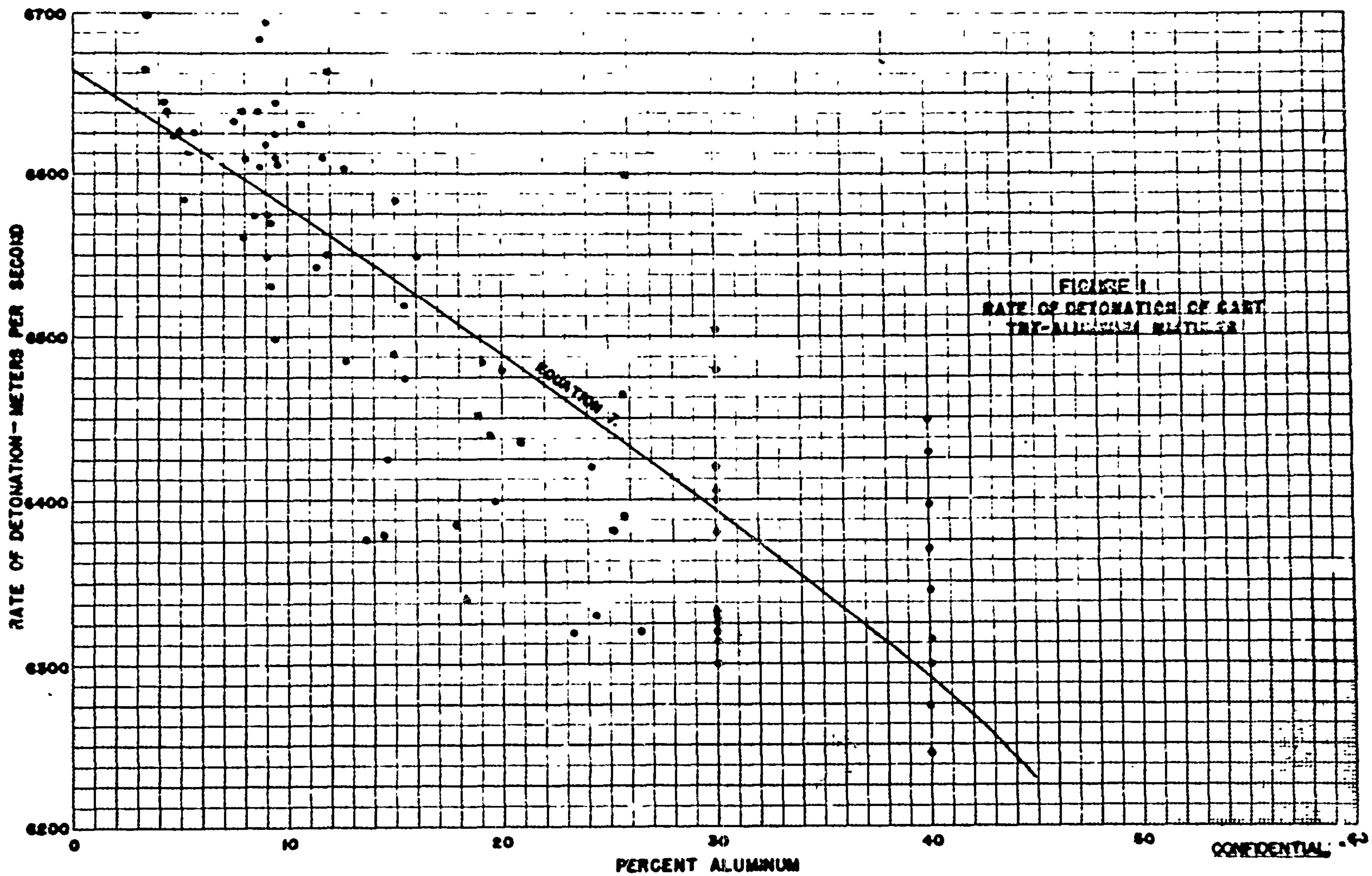
Table A

Heat Extracted by One Mole of Aluminum Particles, Q_a

t micro-sec.	Q_a (calories/mole) C = .0050 cm. T (°K.) 2000	3000	C = .0025 cm. T (°K.) 2000	3000
.1			3596	5711
.2	2487	3637	5299	[illegible]416
.4			7189	11419
.5	4303	6722	-	-
.6			8338	13244
.8			9154	14539
1.0	6089	9558	9766	15510
1.3			10429	16563
1.5	7202	11327	-	-
1.6			10883	17284
2.0			11278	17913
2.5			11562	18362
3.0			11715	18607



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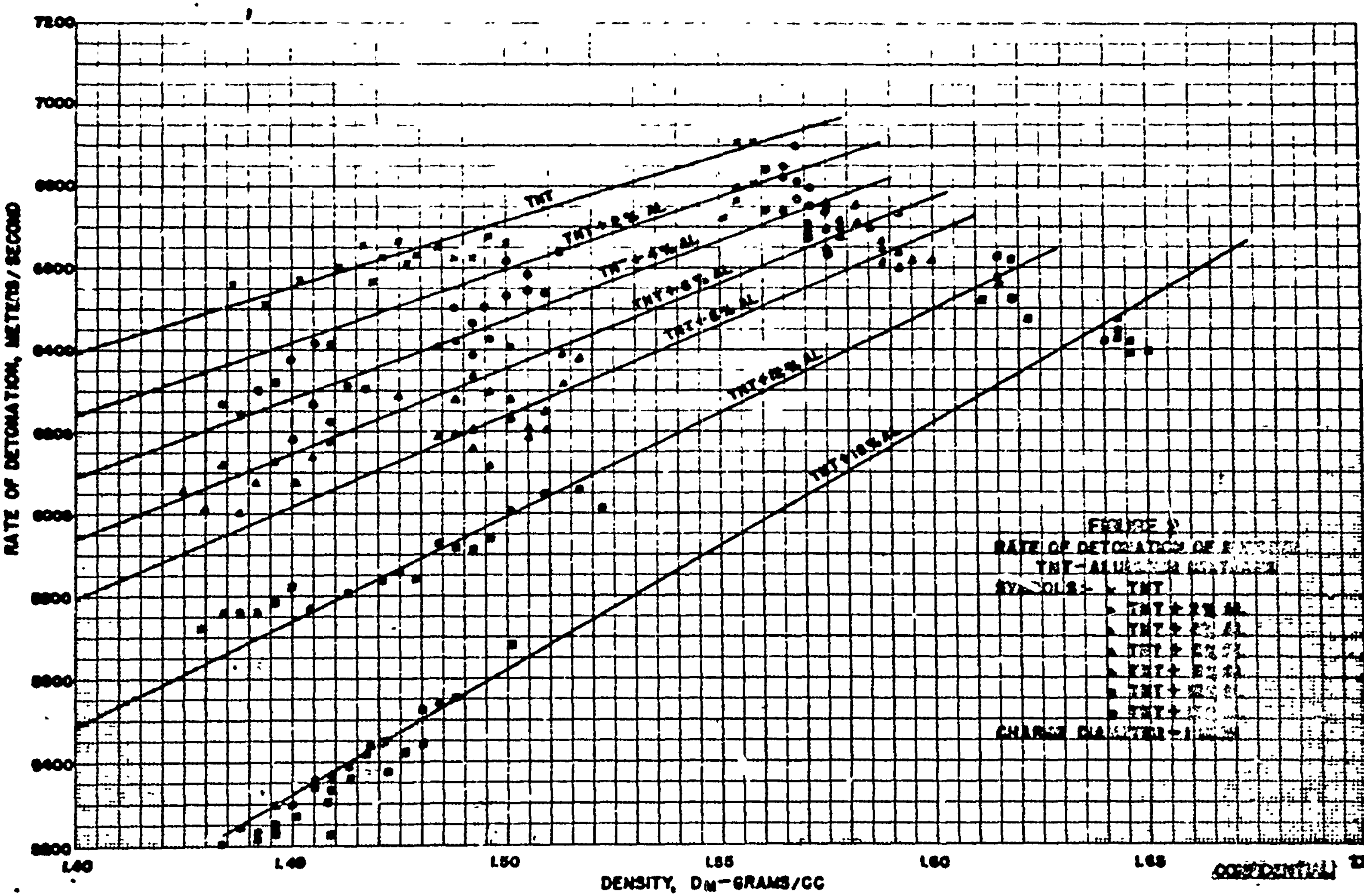

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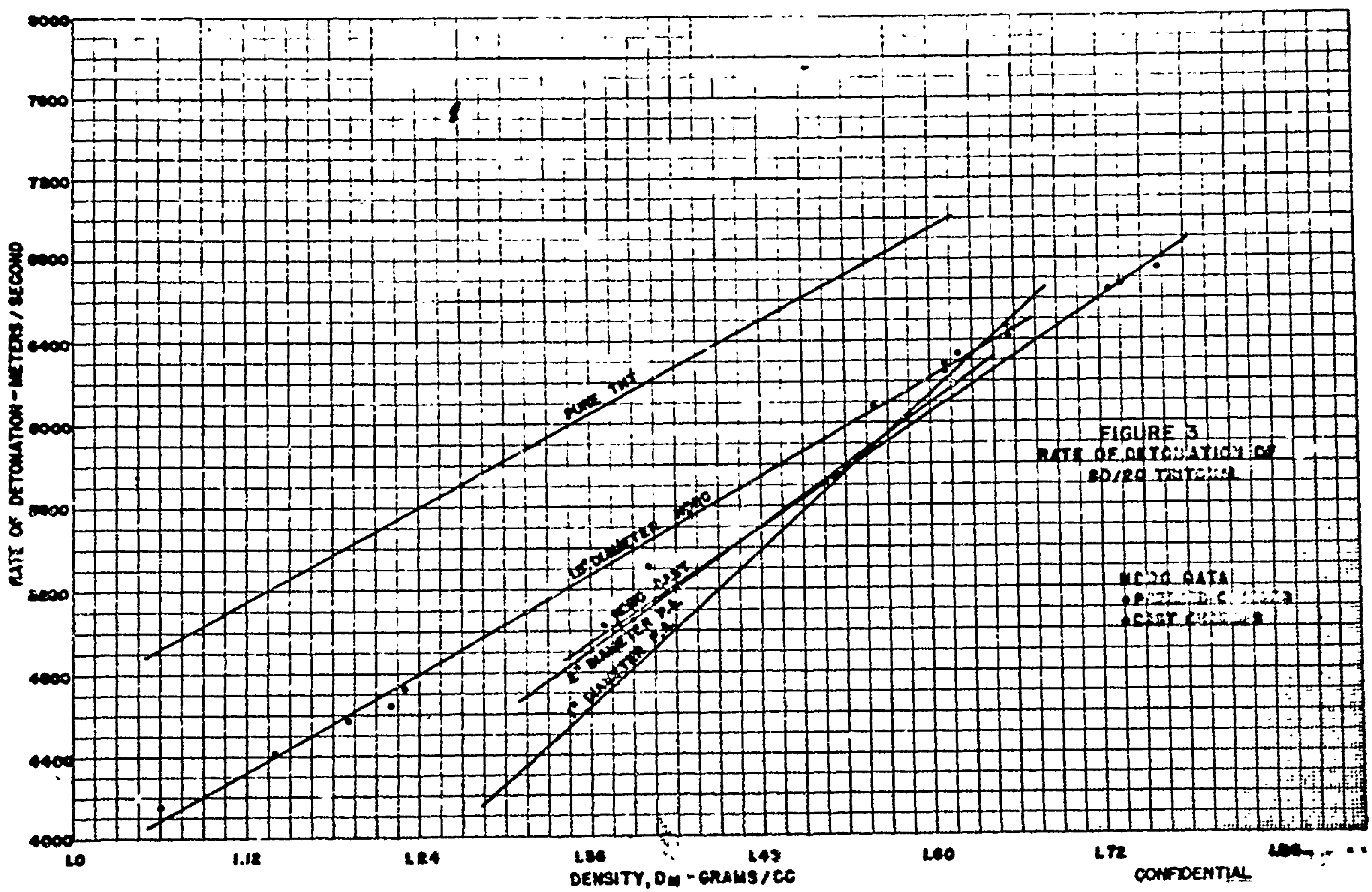

FIGURE 3
RATE OF DETONATION OF 80/20 TRITONAL

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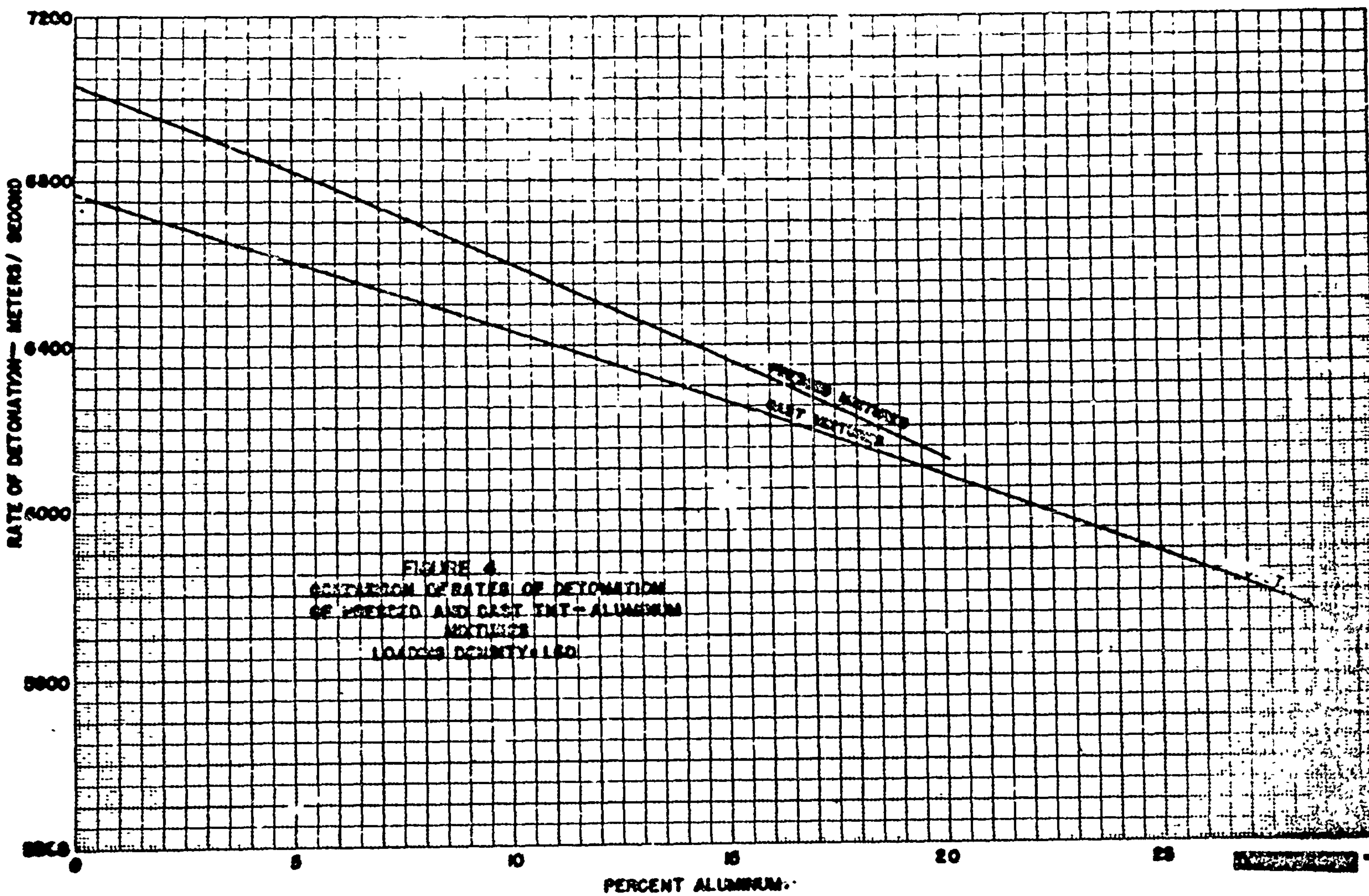
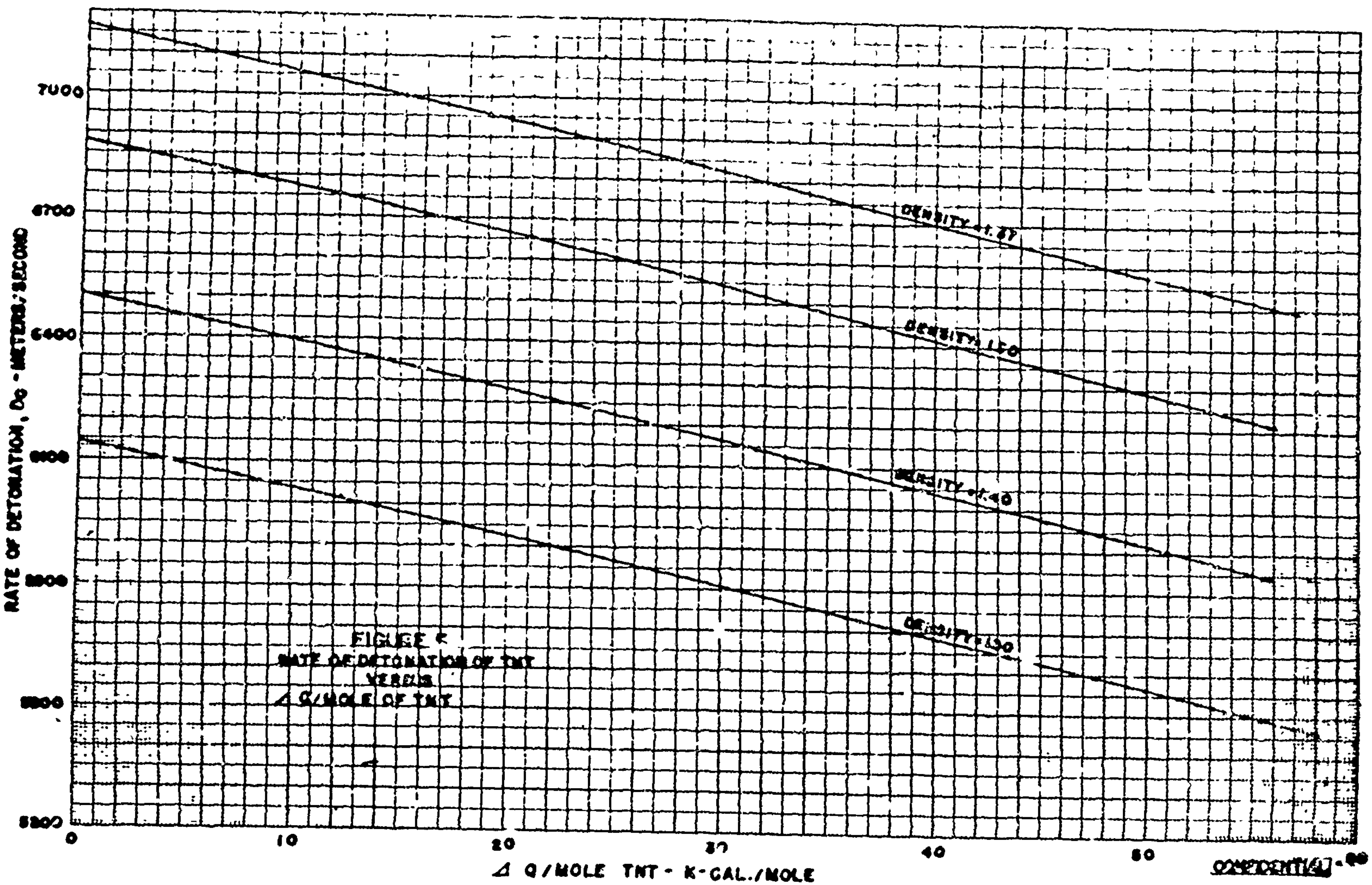


FIGURE 4
COMPARISON OF RATES OF DETONATION
OF PRESSED AND CAST TNT-ALUMINUM
MIXTURES
LOADING DENSITY 1.60



7000
6700
6400
6100
5800
5500
5200
RATE OF DETONATION, D_0 - METERS/SECOND
0
10
20
30
40
50
60
Δ Q/MOLE TNT - K-CAL./MOLE
DENSITY=1.57
DENSITY=1.50
DENSITY=1.40
DENSITY=1.30
FIGURE 5
RATE OF DETONATION OF TNT
VERSUS
Δ Q/MOLE OF TNT
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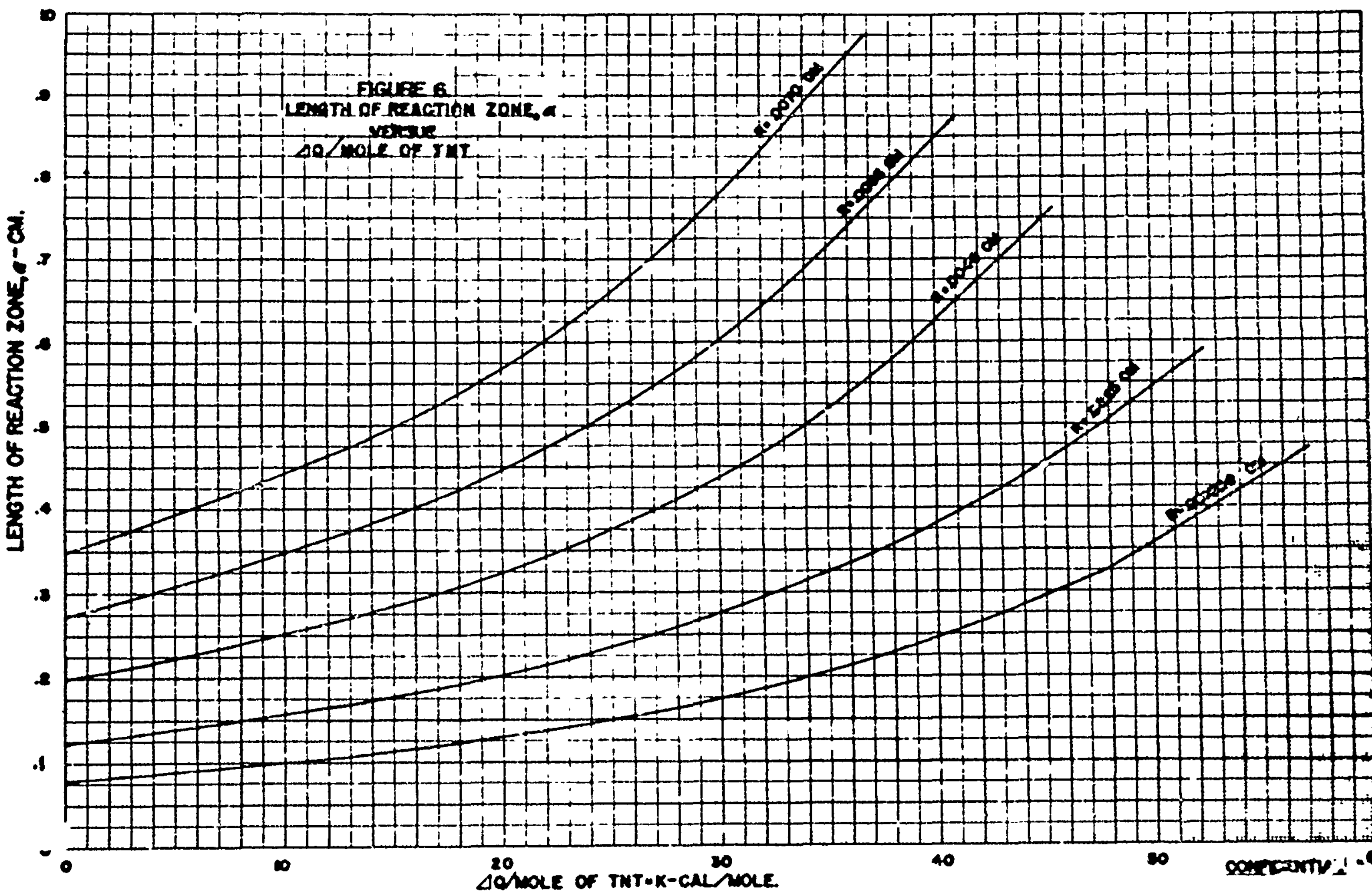
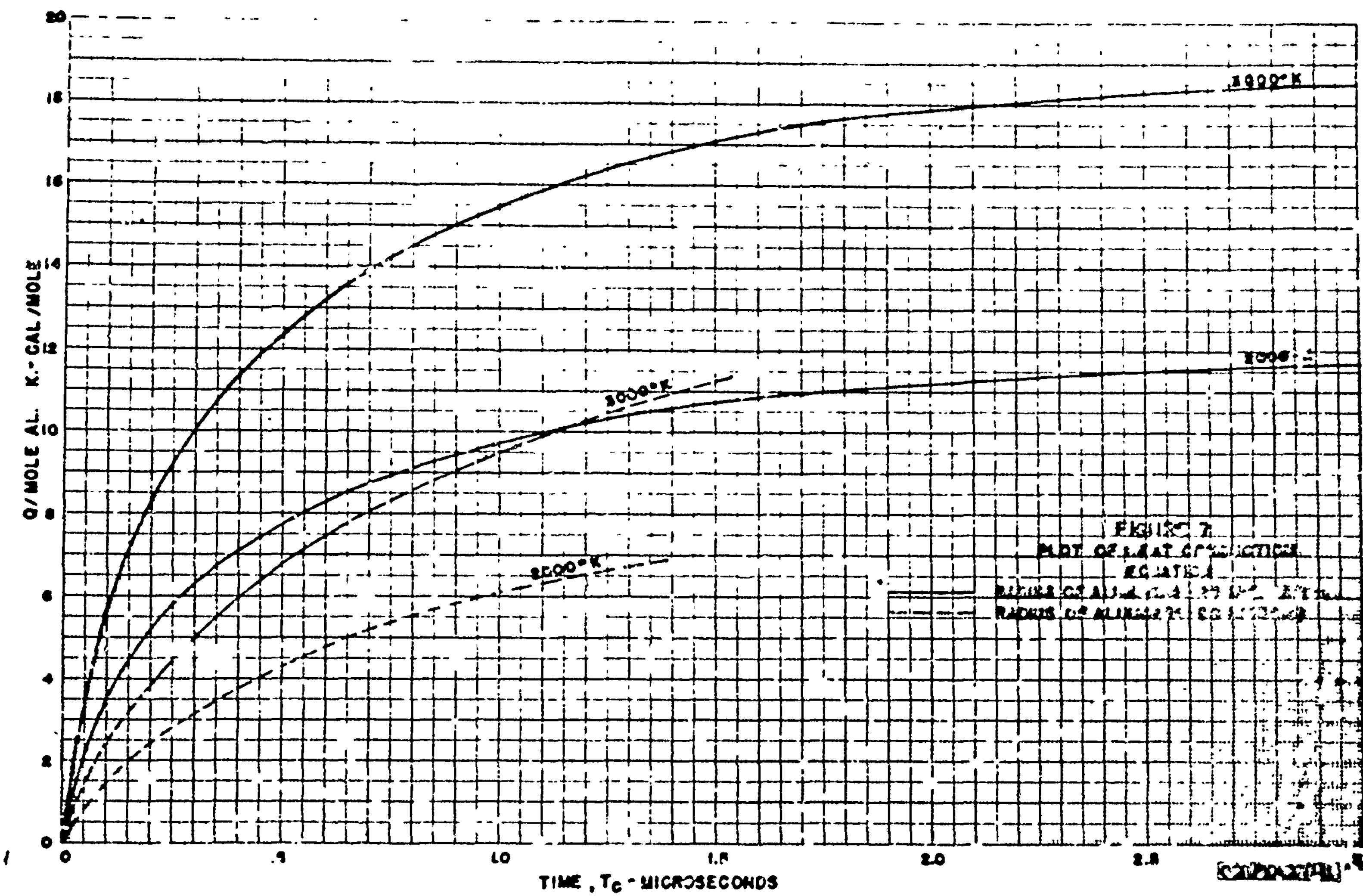


FIGURE 6
LENGTH OF REACTION ZONE, a
VERSUS
ΔQ/MOLE OF TNT
LENGTH OF REACTION ZONE, a - CM.
ΔQ/MOLE OF TNT-K-CAL/MOLE.
0
10
20
30
40
50
60
.1
.2
.3
.4
.5
.6
.7
.8
.9



Q/MOLE AL. K.-CAL/MOLE
0
2
4
6
8
10
12
14
16
18
20
TIME, T_C - MICROSECONDS
0
.5
1.0
1.5
2.0
2.5
3.0

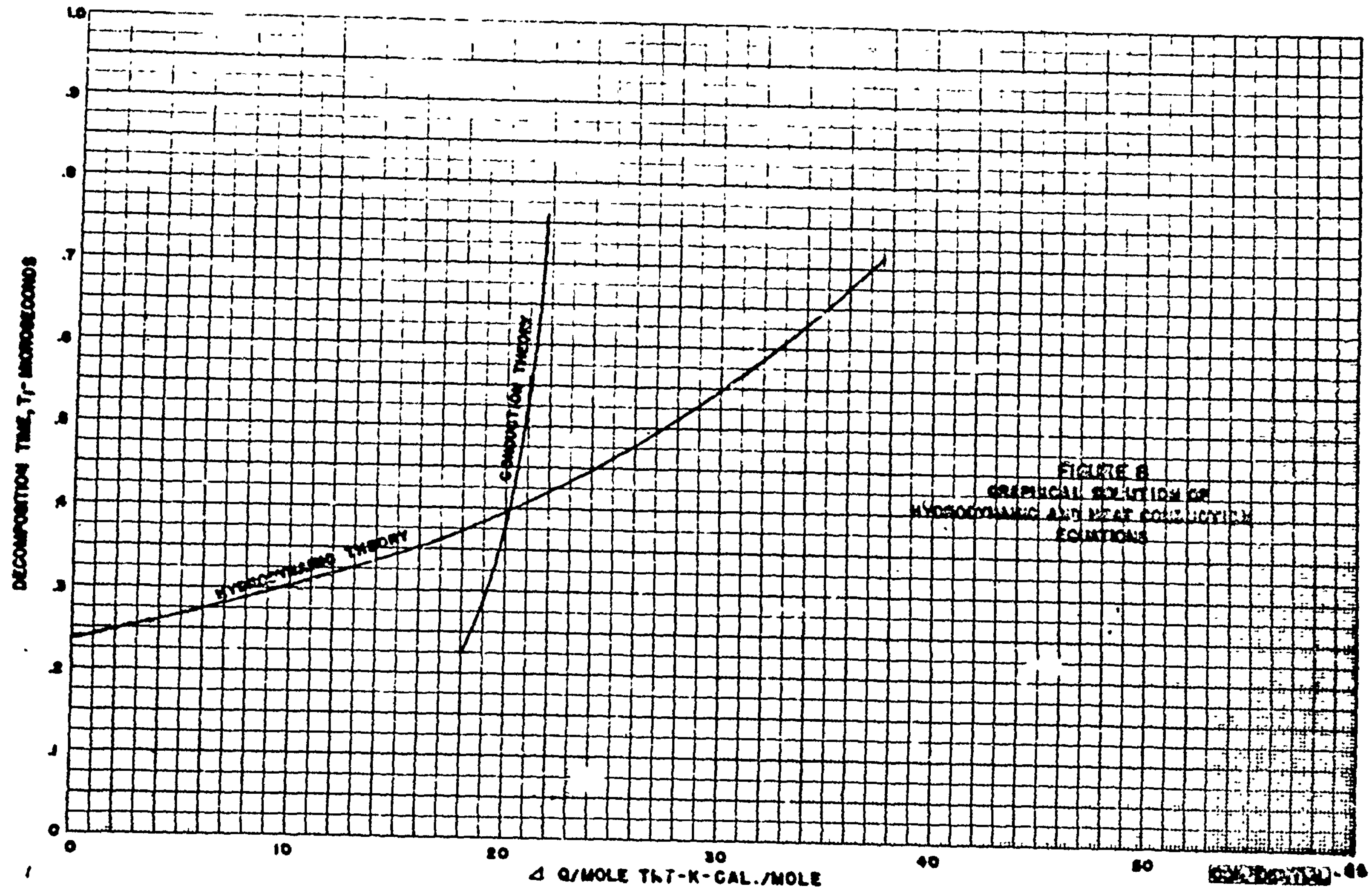


FIGURE 8
GRAPHICAL SOLUTION OF
HYDRODYNAMIC AND HEAT CONDUCTION
EQUATIONS

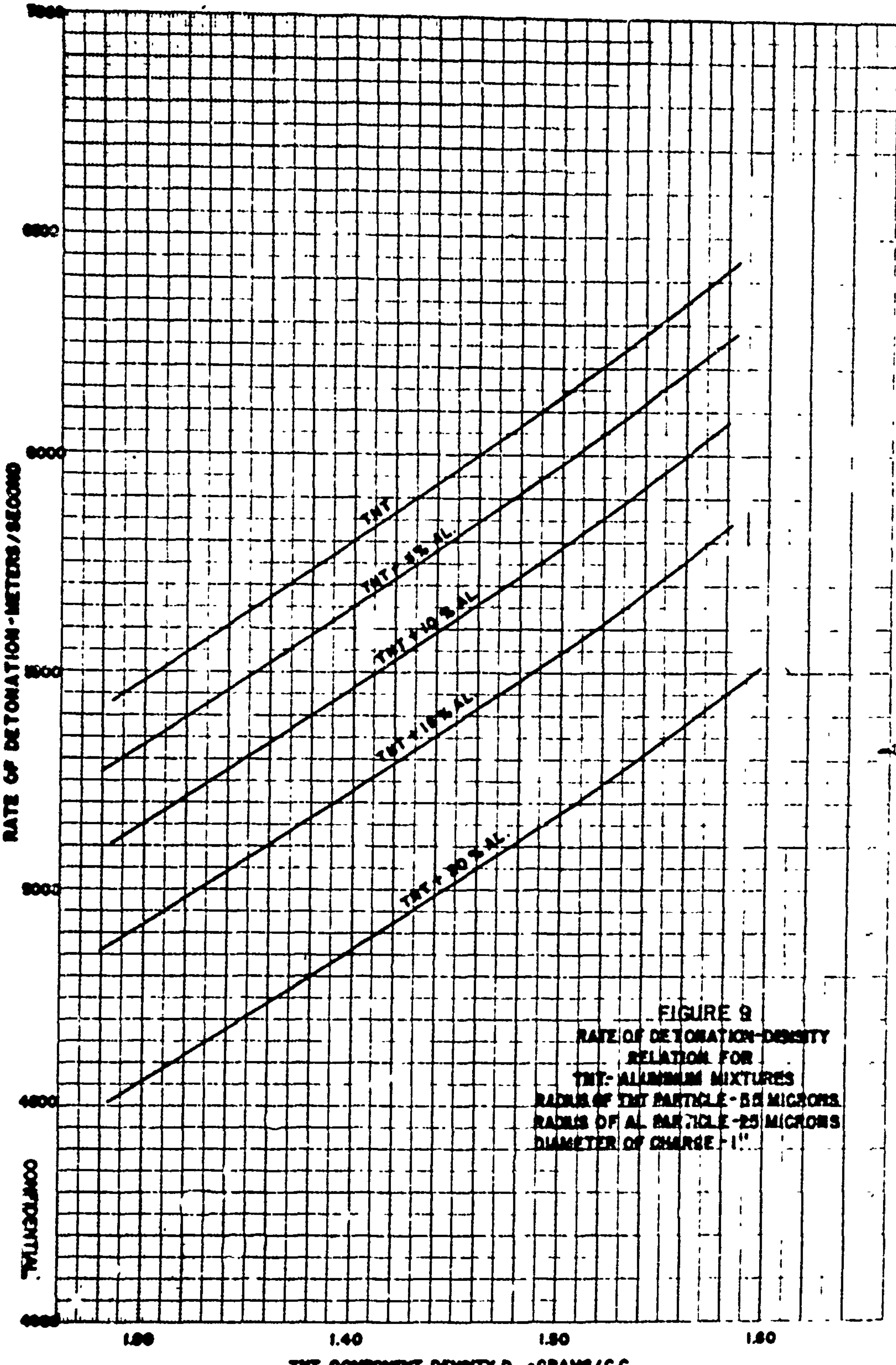
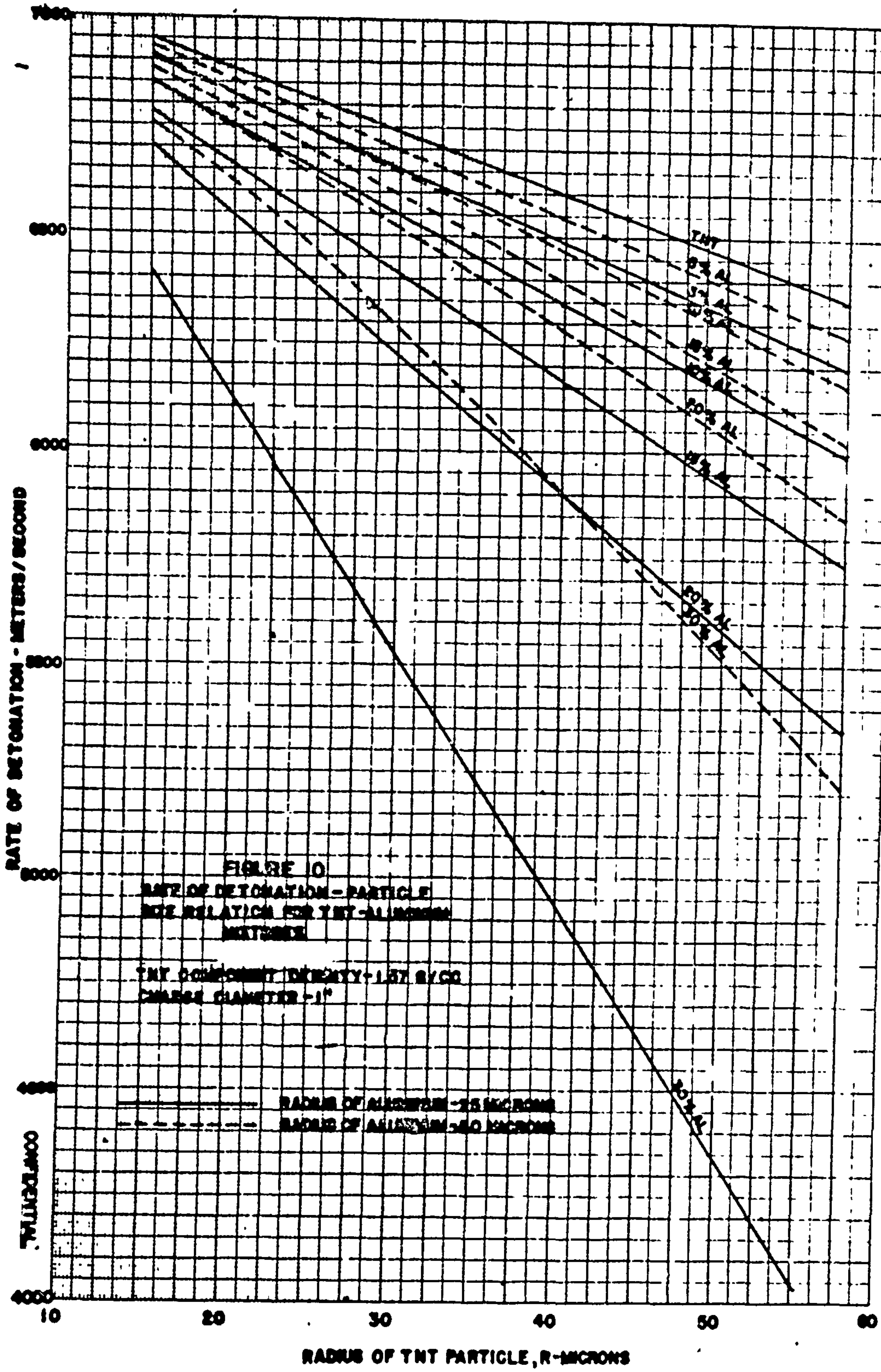
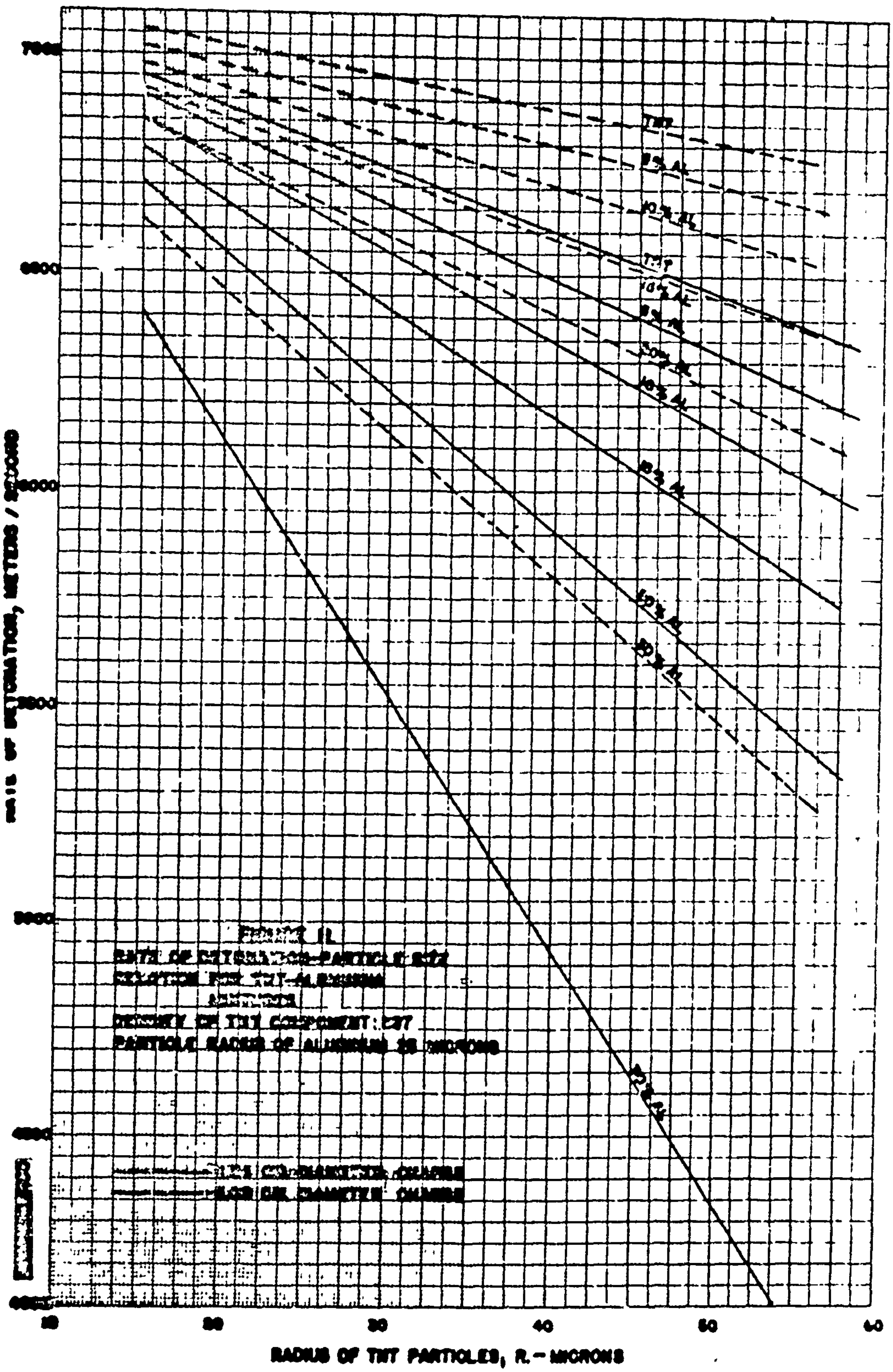


FIGURE 9
RATE OF DETONATION-DENSITY RELATION FOR TNT-ALUMINUM MIXTURES
RADIUS OF TNT PARTICLE - 55 MICRONS
RADIUS OF AL PARTICLE - 25 MICRONS
DIAMETER OF CHARGE - 1"



RATE OF DETONATION - METERS/SECOND
RADIUS OF TNT PARTICLE, R-MICRONS
7000
6800
6000
5000
4000
10
20
30
40
50
60
TNT
FIGURE 10



TNT
5% AL
10% AL
TNT
10% AL
5% AL
10% AL
10% AL
RATE OF DETONATION, METERS / SECOND
RADIUS OF TNT PARTICLES, R.—MICRONS
10
20
30
40
50
60

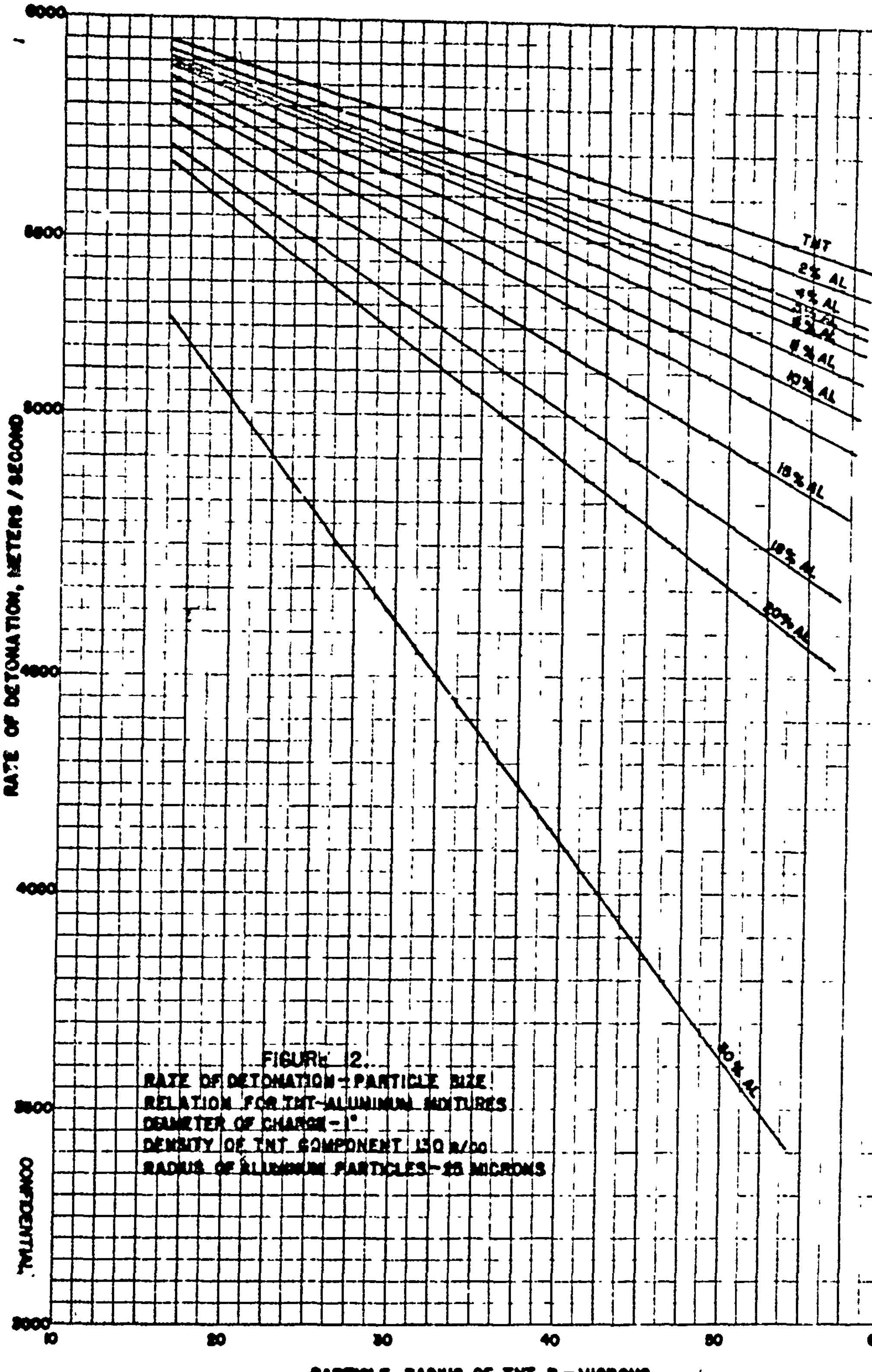


FIGURE 2.
RATE OF DETONATION - PARTICLE SIZE
RELATION FOR TNT-ALUMINUM MIXTURES
DIAMETER OF CHARGE - 1"
DENSITY OF TNT COMPONENT 130 g/cc
RADIUS OF ALUMINUM PARTICLES - [illegible] MICRONS

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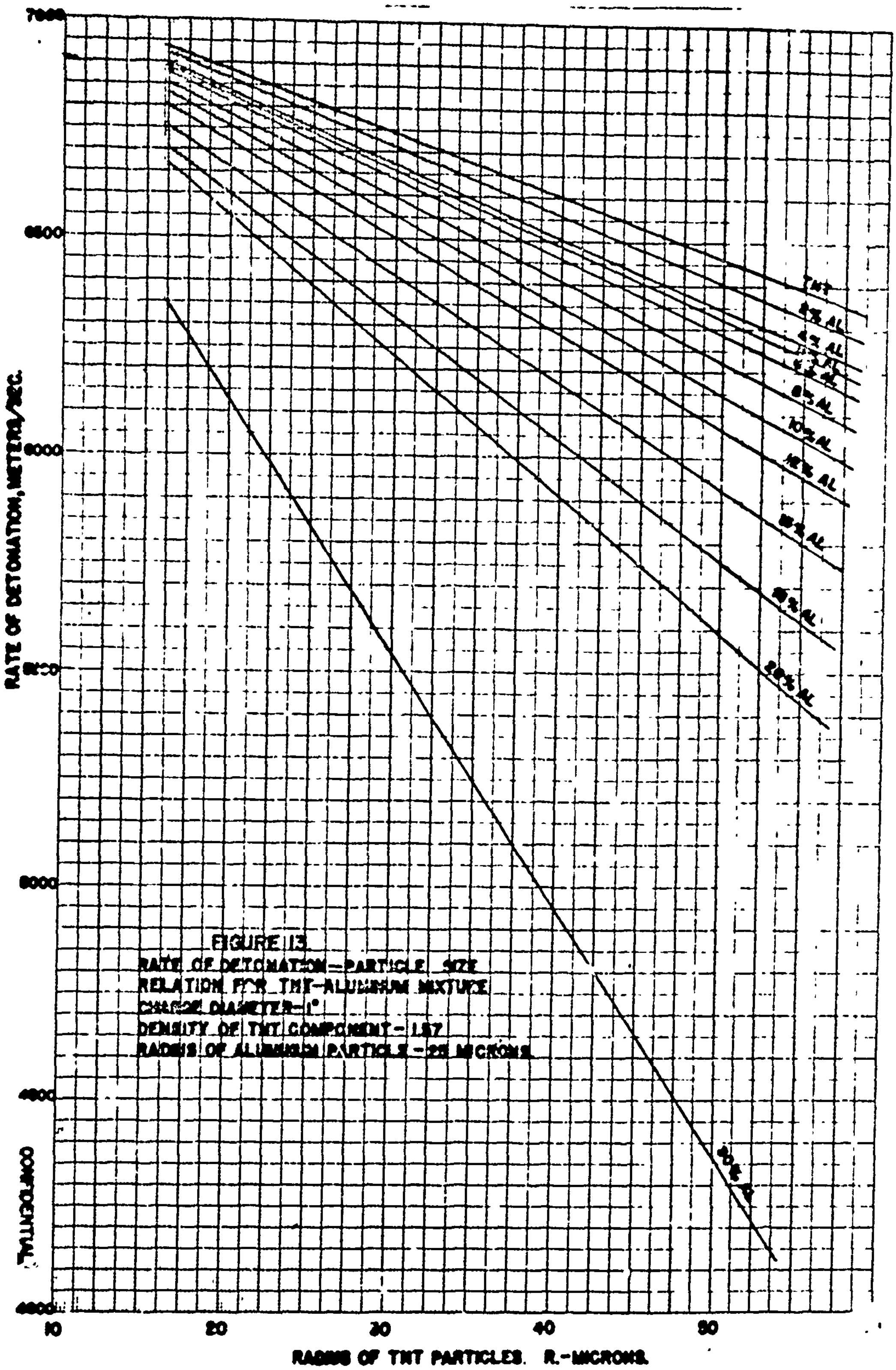

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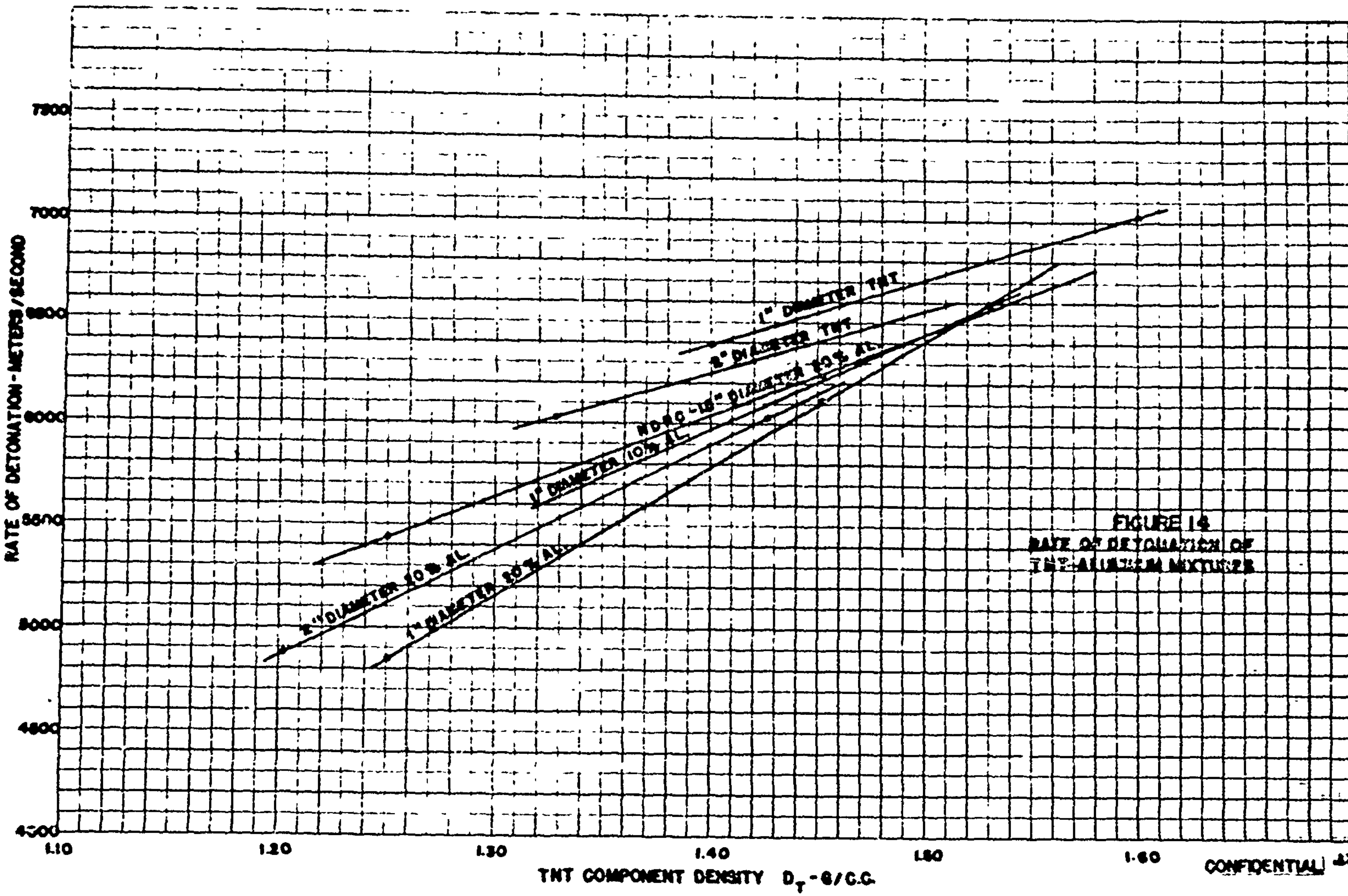

FIGURE 14
RATE OF DETONATION OF
TNT-ALUMINUM MIXTURES

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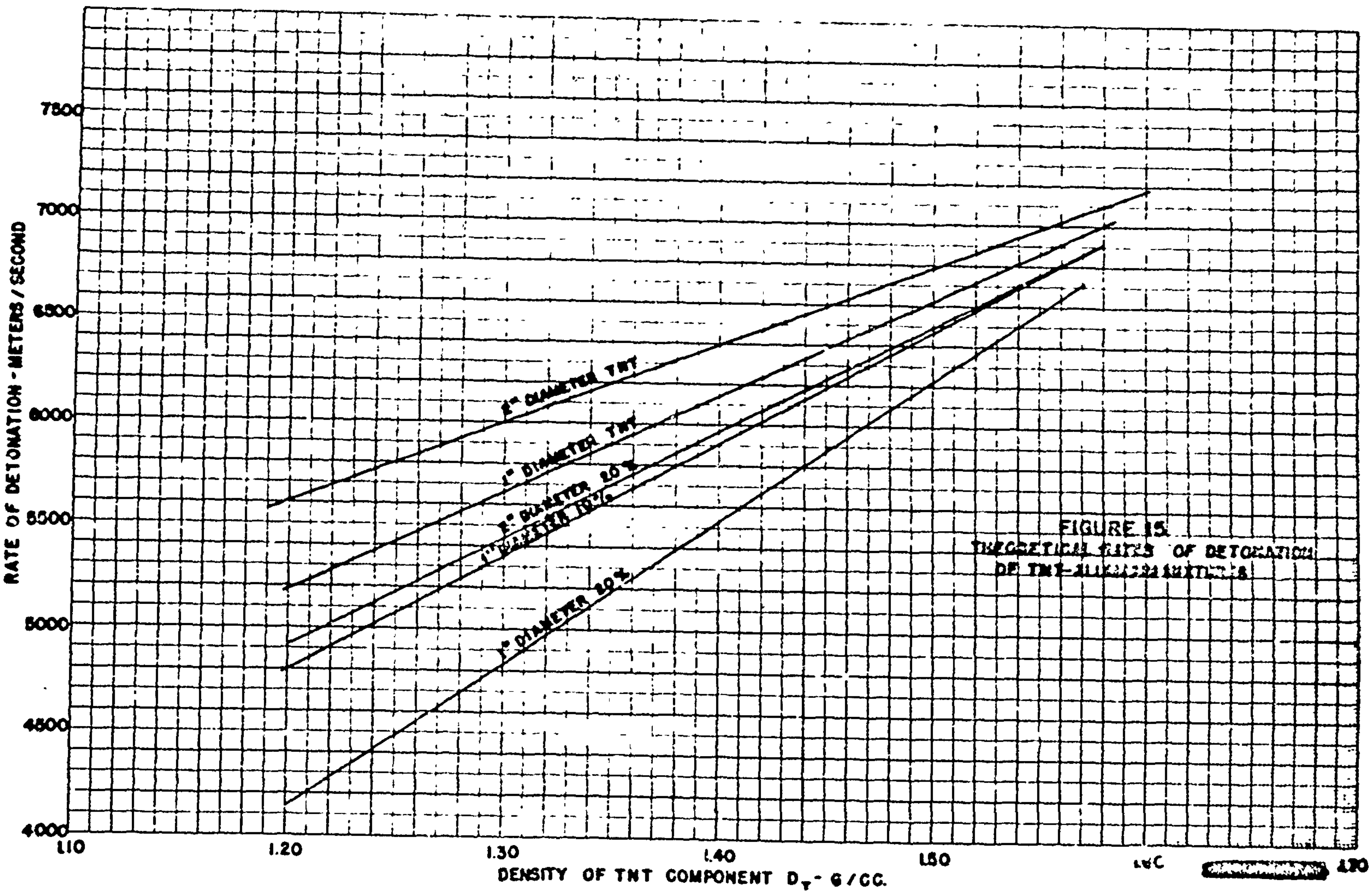
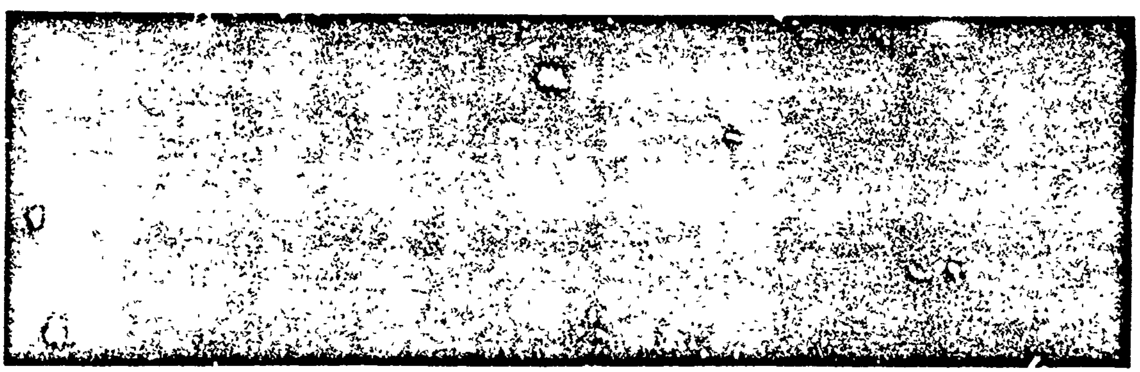


FIGURE 15
THEORETICAL RATES OF DETONATION
OF TNT-[illegible] MIXTURES

[redacted] UNCLASSIFIED

TNT/Aluminum: 94/6

TNT/Aluminum: 85/15



TNT/Aluminum: 75/25

[redacted] UNCLASSIFIED

M-28660	June 1945	PICATINNY ARSENAL	ORDNANCE DEPARTMENT (Tech. 13)
	Radiographs of Cast TNT Aluminum Charg.		(T)